INSTRUMENTAL COLOUR MEASUREMENT OF PORCELAIN LAMINATE VENEERS

An In-vitro Study

WILLIAM GRANT TAYLOR

Thesis Submitted for the Degree of MSc.(Med. Sci)
In the Faculty of Medicine, University of Glasgow

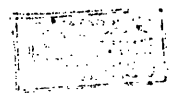
Adult Dental Care Education Group
University of Glasgow Dental School

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 – 1346

ABSTRACT

The choice of shade of tooth coloured restorative materials is very subjective as no quantitative measurement of colour is taken. This can have an effect on the aesthetic success of porcelain laminate veneer restorations, as these are prescribed widely to alter the colour of one or more of the patient's discoloured teeth, to match that of the patient's adjacent teeth. It is therefore extremely difficult for the operator to know which shade to select for the restoration, and in an attempt to alleviate this problem, research has been carried out on the instrumental colour measurement of natural teeth and aesthetic restorative materials to give objective results. The instruments best suited for colour measurement are spectrophotometers and colorimeters. The aims of this study were to establish if the Spectramatch GT spectrophotometer was a suitable instrument for use in the detection of colour differences among porcelain laminate veneers. This study also undertook to determine the effect of various try-in media on the colour of porcelain laminate veneers and to establish the effect of various porcelain laminate veneers on the colour of underlying tabs of various shades used to simulate the crowns of teeth.

Shofu Vintage Body Porcelain was used to fabricate 0.5x12mm discs representing laminate veneers and 2.5x12mm base tabs representing the teeth. Four try-in media (air, distilled water, glycerine & base/try-in paste) were used between the veneers and base tabs. The Spectramatch GT spectrophotometer was used to analyse the



colour of the samples, with the data recorded in C.I.E. L*a*b* notation, and the C.I.E. ΔE colour differences calculated.

The results showed that the Spectramatch GT spectrophotometer was capable of detecting small colour differences between shades, that there were statistically significant differences between air and all three other try-in media, and that shade A3 & B1 veneers were not capable of producing clinically acceptable shade matches when placed over different shades of base tabs, while shade B4 & C4 veneers were of producing clinically acceptable shade matches when placed over different shades of base tabs.

Table of Contents

LIST OF CONTENTS

CHAPTER ONE: LITERATURE REVIEW.

List of Contents (contd.)

List of Contents (contd.)

List of Contents (contd.)

List of Contents (contd.)

Index of Tables

Table

3.1.12 B1 tab & veneer combinations compared to tab B1 with water

3.1.13 B4 tab & veneer combinations compared to tab B4 with water

3.1.14 C4 tab & veneer combinations compared to tab C4 with water

3.1.15 A3 tab & veneer combinations compared to tab A3 with glycerine

3.1.16 B1 tab & veneer combinations compared to tab B1 with glycerine

3.1.17 B4 tab & veneer combinations compared to tab B4 with glycerine

3.1.18 C4 tab & veneer combinations compared to tab C4 with glycerine

3.1.19 A3 tab & veneer combinations compared to tab A3 with base/try-in paste

3.1.20 B1 tab & veneer combinations compared to tab B1 with base/try-in paste

3.1.21 B4 tab & veneer combinations compared to tab B4 with base/try-in paste

Index of Figures

Figure

INTRODUCTION

The choice of shade of tooth coloured restorative materials is very subjective as no quantitative measurement of colour is taken. This can have an affect on the aesthetic success of porcelain laminate veneer restorations, as these are prescribed widely to alter the colour of one or more teeth, to match that of the patient's adjacent teeth. The laminates are generally 0.5 - 0.75mm thick and are made of translucent dental porcelain, which inevitably leads to a certain amount of "shine through" of the underlying tooth colour. It is therefore difficult for the operator to know which shade to select for the restoration to give an aesthetically acceptable result. The Vita Lumin Shade Guide, (Vita Zahnfabrik, Bad Sackingen, Germany), consisting of 16 coloured porcelain tabs, is widely accepted as the standard method of shade selection for indirect restorations, and many manufacturers formulate their products to conform to this guide. The normal method of shade selection is subjective; the operator selects a tab from the guide, which gives the closest visual match to the patient's natural teeth. This shade is then prescribed in the hope that the restoration gives the desired aesthetic result. This method of colour selection is unreliable as there are many factors influencing the operator's perception of the shade including lighting conditions, operatory lighting, surgery décor, colour of clothing, surface texture of the teeth, the weather and the operator's visual aptitude. In an attempt to alleviate this problem research has been carried out on the instrumental colour measurement of natural teeth and aesthetic restorative materials to give objective results. The instruments best suited for colour measurement are spectrophotometers

and colorimeters which, can analyse the spectral reflectance curve of a material and produce numerical data in industry standard C.I.E. colour specifications. The use of instrumental analysis of the shade of patient's teeth may make it possible to measure the colour of the discoloured tooth and the colour of the adjacent teeth and prescribe a restoration of an appropriate shade and thickness that will give an aesthetically acceptable result.

ACKNOWLEDGMENTS

Several people have contributed to this project in many different ways and they all deserve my heartfelt thanks and acknowledgement.

I would like to thank my supervisor, Professor William P Saunders, Professor of Endodontology, University of Glasgow Dental School, for his unflagging encouragement and advice throughout this study. I am also indebted to Professor Saunders for his guidance regarding the statistical analysis used in the study and his overall enthusiasm without which this project would not have reached completion.

I would also like to convey my gratitude to Mr Richard Foye, Senior Technician, Department of Oral Sciences, University of Glasgow, for his expertise and invaluable guidance in the relation to the sample preparation.

Lastly but not least I must express my gratitude to my darling wife Anne and my two beautiful children Lana and Jay for their loving and tolerant indulgence throughout this period of study. I wish to express my

appreciation of their forbearance during the many hours in which I deprived them of my presence, without which this study would not have been possible.

DECLARATION

This thesis, with the exception of the assistance acknowledged herein is the result of my own work.

The work has not been submitted previously and is not currently under consideration in whole or in part of any other degree.

CHAPTER ONE: Literature Review

1.1 Tooth Discolouration

The frequency of discolouration in the human dentition appears to be an increasing phenomenon. This increase may be related to the usage of drugs or other medications during the development of the permanent dentition, the ageing process itself where patients are retaining the natural dentition for their natural lifespan, or other, as yet unknown factors (Jordan *et al,* 1992). The increase in discolouration of anterior teeth in particular has lead to a parallel increase in the patient's demand for cosmetic and aesthetic dental restorations, to meet the pressures placed on them by modern society's demand for attractive smiles. Fortunately there has been a simultaneous revolution in the materials and techniques available to the clinician that are capable of fulfilling even the most discerning of patient's aesthetic aspirations.

1.1.2 Types of Tooth Discolouration

Jordan *et al*, (1992), have reviewed the types of dental discolouration that are frequently observed (Jordan *et al*, 1992). These are:

(a) Tetracycline discolouration

(b) Hypoplastic discolouration

(c) Fluorosis staining

(d) "White spots"

(e) Nonvital discolouration

(f) "Ageing" discolouration

Tetracycline Discolouration

This is caused by the systemic use of the tetracycline group of antibiotic drugs during the developmental stages of the permanent dentition or passed from the mother to the unborn child during pregnancy. It can produce a range of different coloured bands in teeth, including browns, greys and yellows of varying intensities, depending upon the nature and quantity of the medication prescribed.

Hypoplastic Discolouration

Hypoplastic discolouration can be usually be identified as horizontal pits or crevices in the enamel surface. These anomalies are caused by disturbances during the enamel formation affecting calcium deposition. The cause can be local or systemic agents, or hereditary disease.

Fluorosis Staining

This is a form of enamel hypoplasia resulting from ingestion of high fluoride levels from water supplies or toothpaste during tooth development, and is evident as cloudy or diffuse areas of mottled white in teeth.

White Spots

This is a form of enamel hypoplasia and can be identified as a very densely opaque, irregularly rounded area on the labial enamel surface.

Nonvital Discolouration

The main causes of nonvital discolouration are necrosis of the pulp and endodontic therapy. Blood, other organic material or medicaments left in the pulp chamber may cause discolouration of the tooth. Blood, extravasated into dentinal tubules breaks down and stains the dentine.

Ageing Discolouration

As people age the colour of their teeth will usually become darker. This may be because of cracks in the enamel leading to staining by such products as tea, coffee, wine or tobacco, or by the formation of secondary or reparative dentine, and increased mineralisation of the intertubular dentine.

The clinician must determine the nature of the discolouration and then diagnose the physical extent i.e. is the discolouration confined to the superficial enamel thickness, or is it concentrated in the deep dentinal layers? This diagnosis will determine the extent and complexity of the treatment, and define the nature of the restoration utilised to ensure an acceptable result aesthetically.

1.1.3 Treatment Options for Tooth Discolouration

There are currently six conservative treatment options available for discoloured dentitions. These are:

(a) Direct composite resin veneers

(b) Enamel microabrasion

(c) Vital bleaching

(d) Nonvital bleaching

(e) Indirect veneers (composite resin or ceramic)

(f) Indirect or direct veneers combined with bleaching

The treatment protocols listed above each have their own indications and limitations and the clinician should select the most appropriate restorative procedure for each specific case. The indications for the use of these treatment options as advocated by Jordan *et al*, (1992), are:

Direct Composite Labial Veneers

The indications for direct composite labial veneers are:

(a) White spots

(b) Severe fluorosis discolouration

(c) Severe hypoplastic discolouration

In each of these instances the discolouration is confined to the enamel thickness and does not extend into dentine. The operator may remove 0.5mm of the labial enamel prior to acid etching the enamel to facilitate the direct bonding of the composite resin.

Enamel Microabrasion

The main indication for enamel microabrasion as described by Croll *et al*, (1989), is in the conservative treatment of fluorosis white spots. These "snow-cap lesions" are

confined to the upper 75μm of the labial enamel, and may be removed with a dilute solution of hydrochloric acid (18%) in an abrasive medium (pumice), which will demineralise and remove the superficial enamel (Croll, 1989).

Vital Bleaching

This is the most conservative protocol for the treatment of discoloured teeth and indications include:

(a) Light yellow to grey uniform tetracycline staining

(b) Fluorosis discolouration

(c) Acquired superficial discolouration (staining of unknown origin)

(d) Haemorrhagic discolouration (discolouration caused by severe trauma to the tooth at early age associated with rupture of pulpal blood vessels and extravasation of erythrocytes into the dentine tubules, with severe cases resulting in pulp death requiring root canal treatment and non vital bleaching).

The two treatment options are "office bleaching" and "home bleaching". Office bleaching is a chairside procedure, involving the use of hydrogen peroxide (30%), as the bleaching agent, placed on the area of discolouration over a number of visits, until an acceptable aesthetic result is achieved (Goldstein, 1997).

Home bleaching requires an impression of the discoloured dentition to be taken to facilitate the laboratory fabrication of a soft tray 0.2mm thick extending 1mm beyond the discoloured hard tissues (Haywood, 1997). A 10% carbamide peroxide gel is applied to the fit surface of the tray, which the patient wears every night during sleep

until the desired shade is achieved.

Nonvital Bleaching

This option can be used to treat postendodontic discolouration, which may have been caused by the incomplete removal of organic material or medicaments used during endodontic therapy. The treatment may involve removal and replacement of any inadequate root filling materials prior to internal bleaching of the pulp chamber, followed by bleaching of the labial surface of the tooth using the techniques and materials described in vital bleaching. This procedure is repeated over a number of visits until the desired aesthetic result is achieved. A modification of this technique is "walking bleaching", where the pulp chamber is filled with a mixture of sodium perborate and water, and the access opening is then temporarily sealed (Rotstein *et al.* 1991). The procedure is repeated at a number of subsequent weekly visits until the desired shade is achieved.

Indirect Ceramic or Composite Resin Veneers

These restorations are indicated for intact worn, discoloured, malaligned or malformed anterior teeth. The technique involves removal of 0.5mm of the labial enamel surface to allow sufficient labial space to place the restoration without altering the patients facial profile, and a chamfer finish margin, cut on the mesial, distal and cervical, to enable accurate placement of the veneer (Calamia, 1985). Elastomeric impressions of the dentition are taken to facilitate the fabrication of 0.5mm thick composite resin or porcelain veneers in laboratory. The veneers are resin-bonded to the acid etched enamel of the teeth at a subsequent visit.

Laboratory fabricated light-cured composite resin veneers may be utilised for this procedure, but they are not as acceptable aesthetically or as durable as porcelain laminate veneers.

Porcelain laminate veneers have a number of major clinical advantages, (Jordan *et al*, 1992):

(1) Highly aesthetic with a translucency and surface texture very similar to natural teeth.
(2) Excellent gingival response because of the biocompatible nature of the material.
(3) Ultraconservative because of the small amount of labial enamel reduction necessary to produce an aesthetically pleasing restoration.
(4) Durable and fracture-resistant when placed in non-load bearing situations.

The main disadvantage of porcelain as a restorative material for laminate veneers is that it is brittle in thin cross section.

Combined Bleaching-Porcelain Veneer Technique

This treatment option can be used for severe tetracycline discolouration where the tooth colour is so dark that the translucent porcelain veneer would not mask the underlying colour sufficiently to give an acceptably aesthetic result without prior "lightening" of the tooth by bleaching. The treatment after bleaching would then be carried out as for normal indirect porcelain laminate veneers.

1.2 COLOUR SCIENCE

1.2.1 History of Colour Science

The Greek philosopher Aristotle first approached colour as a science in the fourth century BC, where records have shown that he discussed the importance of light and colour and their relationship to one another with his students (Lemire and Burk, 1974). Isaac Newton discovered in 1666 that white light could be broken down into a rainbow of colours by passing it through a prism (Lemire and Burk, 1974). It was not until the early nineteenth century that Ewald Hering described the colour circle familiar to artists (Freedman and McLaughlin, 1990). Sigfrid Forsius first described the nature of colour as three-dimensional in 1611 and it is this three-dimensional model which forms the basis of all modern colour notations (Sproull, 1973).

1.2.2 Nature of Colour Perception

The complex nature of colour encompasses not only objective but also subjective phenomena, which are bound by the laws of nature. Colour can be measured objectively, but human colour perception is accepted as being subjective. The problems in relating the objective to the subjective occur when the physical facts of colour such as measurement of reflectance as a function of wavelength are translated to the psychological, (i.e. perceptual). A total lack of light will result in a lack of perception of any colour. If no object is present the colour cannot exist, and if the human observer closes their eyes no colour can be perceived. The three components are interdependent, the colour we see is determined by the radiation from the light

source as modified by the object and received and interpreted by the human eye (Lemire and Burk, 1974). Thus the science of colour was formed in an attempt to establish an international psychophysical method of colour specification (Sproull, 1973). Light can be totally natural in that it is derived from the sun, either directly or by reflection, or artificial such as electric incandescent lighting or derived from the burning of petroleum products or many other sources. Scientifically, light is described as visible energy or radiant energy and is part of the electromagnetic spectrum. A characteristic of radiant energy, and therefore also of light, is wavelength. This attribute is used in the specification of light, in that one unit of length is called a nanometer, (nm); one millimeter contains one million nanometers. The part of the spectrum of electromagnetic energy visible to the human eye is only a very small region occupying from approximately 380 to 780 nm. This region is called the visible spectrum and it is this region that we are concerned with in colour science and communication. The area immediately beyond this region towards the longer wavelengths is the infrared region and towards the shorter wavelengths is the ultraviolet region, both of which are invisible to the naked eye. The human eye sees the visible spectrum of light as the colour red in the long wavelength towards 780 nm and violet in the short wavelength around 380 nm.

1.2.3 Munsell Colour System

In 1905 an A.H. Munsell, an artist and art teacher, enhanced colour communication with the development of the Munsell Colour Order System, a visual colour order

system. This system is a three-dimensional representation of colour in which he defined the nature of colour in terms of Hue, Value and Chroma (Munsell, 1926). He described the three parameters as (Miller, 1987):

(a) Munsell Hue, being the name of the colour: the quality by which one family is identified from another, such as red from yellow.

(b) Munsell Value, the lightness of the colour: this quality identifies a light colour from a dark one.

(c) Munsell Chroma, the strength of a colour: the quality by which a weak colour from a strong colour is defined.

This system consisted of a large number of paper chips, classified according to the three parameters, which could be used for visual comparisons to a specimen colour. Munsell updated this system and renamed it the Munsell Renotation System, which is still used today to describe colours. The Munsell System is a decimal-based notation system by which any colour can be recorded visually, specified and communicated. In this system any given colour is expressed as a letter number combination (H/VC), where H is hue, V is value and C is chroma, as visually evaluated using Munsell Colour Charts.

There are ten basic Hue families which are identified by uppercase symbols as follows:

R	-	Red	BG	-	Blue Green
YR	-	Yellow Red	B	-	Blue
Y	-	Yellow	PB	-	Purple Blue
GY	-	Green Yellow	P	-	Purple
G	-	Green	RP	-	Red Purple

Value indicating the lightness or darkness of the colour is given a scale of zero for absolute black to ten for absolute white.

Chroma, defining the strength of or weakness of the colour, is the degree of departure from neutral grey of the same Hue for any given Value.

The simplicity of the Munsell System is the reason for its extensive use in art, science, education and industry.

1.2.4 International Commission on Illumination (C.I.E.)

In 1931 the C.I.E., (International Commission on Illumination, Central Bureau of the C.I.E., Vienna, Austria), defined a series of standards that would enable an internationally accepted psychophysical method of colour communication where colours could be determined instrumentally and mathematically.

1.2.4a) C.I.E. Standard Illuminant

The spectral energy distribution curve of a specific light source can be derived by a spectroradiometer. This can be shown in a graphic form as a curve indicating the relative amount of light emitted at each wavelength by the light source. For many years artists favoured northern daylight as the ideal light source for their work and planned their studios accordingly, but other workers favoured other light sources such as fluorescent or incandescent lighting depending on their individual

requirements. The need for a scientific approach to colour measurement brought about the standardisation of specific light sources, as different light sources emit different radiant energy at different areas of the spectrum. Light sources emit varying brightness and hue, bright blue daylight, yellowish incandescent light and so on. In order to quantify colour, the light source and other factors were standardised to enable scientific colour communication. The colour quality of a light source is expressed in terms of the Kelvin temperature scale (K). The first such standard light source is referred to as the black body, which is usually a hollow sphere whose interior is black with a small opening. Taking the actual Celsius temperature of the black body and adding 273 arrives at the Kelvin value. The spectral power distribution and colour of the black body is affected only by temperature, as it is heated it changes colour. At low temperatures the opening is dark red and as it is heated to higher temperatures the yellower and lighter it becomes until it is bluish-white. C.I.E. Standard Illuminant A (International Commission on Illumination, Central Bureau of the C.I.E., Vienna, Austria) is derived from this black body, which has a colour temperature of 2856 K, and where the spectral distribution curves were standardised so that the spectral power is one for all temperatures at 560nm. The spectral power distribution of Standard Illuminant A is similar to that of an incandescent lamp. The other commonly used Standard Illuminant is C.I.E. D65 (International Commission on Illumination, Central Bureau of the C.I.E., Vienna, Austria) which has a standardised colour temperature of 65000 K and closely represents average daylight. These standard illuminants are used in the calculation of colour parameters by instruments and computers, but there are artificial light sources available which may closely represent these conditions.

1.2.4.b) C.I.E. Standard Observer

The observer, as so termed in colour measurement is the human eye. The eye has a variable aperture (the iris) that controls incoming light; behind the iris is the lens with a changeable focus. The lens focuses the image on the retina, which has two different kinds of light sensitive receptors, called cones and rods. The cones are responsible for vision during the day and colour vision and the rods are responsible for vision during twilight. The rods and cones are not dispersed evenly over the retina, there is a one area called the fovea which contains only cones. There are three types of cones that are sensitive to the three primary colours of light i.e. red, green and blue. The observed image is always focused on the centre of the fovea. The colour perception is not the same outside the fovea as it is inside and that has an important bearing on the angle of viewing. In 1931 the C.I.E., (International Commission on Illumination, Central Bureau of the C.I.E., Vienna, Austria), defined the 2^0 Standard Observer which as the name suggests used a 2^0 field of view. The C.I.E. added the 10^0 Standard Observer in 1964 to give a supplementary field of view. To illustrate the difference between the two observers, a 2^0 field of view would view a 1.7cm circle at 50cm (reading distance), and a 10^0 would view an 8.8cm circle at 50cm. The C.I.E. recommends that the 2^0 Standard Observer is used for viewing angles of 1 to 4^0, and the 10^0 for angles greater than 4^0. These standard observers are used in the measurement of colour and the computation of colour values.

1.2.4.c) C.I.E. Colour Matching Functions

The colour-matching functions are calculated for the 2^0 and 10^0 standard observers. These functions are intended to correspond to the spectral sensitivity curves of the human eye, and each Standard Observer has three separate colour matching functions. x (λ) has a high sensitivity in the red wavelength region, y (λ) has a high sensitivity in the green wavelength region and z (λ) has a high sensitivity in the blue wavelength region. The colours that are seen by the human eye are the result of a combination of these three stimuli.

1.2.4d) C.I.E. Tristimulus Values

The tristimulus values are measured and determined by the following method:
Light with spectral distribution (**A**) is incident on sensors with spectral sensitivity (**B**), whose filters divide the light into wavelength regions corresponding to the three primary colours and the sensors output the tristimulus values, (X, Y and Z), (**C**). Thus **C = A x B**.

1.2.4.e) C.I.E. Colour Spaces

Various different colour spaces or methods of describing colour and light numerically can be calculated from the tristimulus values. In 1931 the C.I.E. defined the Y x y colour space based on the XYZ tristimulus values, where Y is the lightness

and is identical to the Y tristimulus value, and x and y are the chromaticity coordinates calculated from the tristimulus values. The Y x y colour space can be represented as a three dimensional solid. The C.I.E. also defined the x, y chromaticity diagram, a two-dimensional graph, which is independent of lightness in order to make the information more accessible visually. In 1976 the C.I.E. devised the L*a*b* colour space to provide more uniform colour differences in relation to visual differences. The L* indicates the lightness, the a* indicates red in the + and green in the -, and the b* indicates yellow in the + and blue in the -. The C.I.E. defined the a* b* chromaticity diagram, a two dimensional graph which is independent of lightness, and the L*a*b* colour space which can be envisaged as a three dimensional solid.

1.2.4.f) C.I.E. L*a*b* Colour Difference (ΔE)

The ΔE Colour Difference between any measured two samples is calculated from the L*a*b* colour space values using the following formula:

$$\Delta E^{*}ab = \sqrt{(\Delta L^{*})^{2} + (\Delta a^{*})^{2} + (\Delta b^{*})^{2}}$$

In this formula ΔL* is the difference in lightness between the two samples, Δa* the difference in the red-green value and Δb* the yellow-blue.

1.2.5 Samples

In this section all objects that light may fall upon will be referred to as samples as a convenient term during description of the substance and surface of various materials and how it may influence light and perceived colour.

All samples alter the incident light, in that as the light that falls upon them, they modify the incident light and appear coloured. The coloured appearance is produced because the samples absorb part of the light, which is generally emitted as thermal radiation. The rest of the light is either transmitted or scattered. The scattered light is also partly reflected. Samples can be divided into three groups (Berger-Schunn, 1994):

(a) Transparent samples: Such samples absorb part of the illuminating light and the other part goes through the sample unscattered; such samples include coloured glasses and transparent plastics. Because transparent surfaces have a different refractive index than air, part of the light is reflected at the air-sample surface. About 4% of the incident light is reflected.

(b) Translucent samples: Samples that not only absorb part of the incident light and transmit the other part, but also scatter part of the nonabsorbed light, are called translucent; such samples include lamp panels and lamp shades. The scattered light is partly transmitted and partly reflected, and because of the difference in the refractive indices between air and sample this amounts to about 4% reflected light.

(c) Opaque or reflecting samples: Opaque samples either absorb the incident light, or reflect it. No light is transmitted through opaque samples. Many objects

surrounding us are opaque including car paints, painted walls and textiles etc.

Samples look coloured because the colorants in them absorb part of the incident light. Depending on the type and amount of colorants used, the different wavelengths of the incident light are differentially absorbed. The radiation that is not absorbed is reflected and is seen by the human eye as colour. The reflectance of the sample can also be measured instrumentally. If the percentage of light reflected at each wavelength is measured, the values can then be plotted on a graph as a reflectance curve.

1.2.6 Metamerism

The colour of an object is dependent on the light under which it is viewed. A problem can arise in colour measurement and reproduction when two objects appear to be the same under one lighting condition, such as natural daylight, and different under another light source such as incandescent room lighting. This phenomenon is known as metamerism. Metameric objects have different spectral reflectance characteristics, but the resulting tristimulus values are the same under one light source but different from each other under another. This could be illustrated by examining samples under Standard Illuminant D65 where both samples had the same L*a*b* values, but produced different values under Standard Illuminant A. Examination of the spectral reflectance graphs of both samples with a spectrophotometer would reveal two entirely different spectral reflectance curves.

1.2.7 Colour Measuring Instruments

There are currently two distinct types of instrument used for measuring colour in industry and research, spectrophotometers and colorimeters.

1.2.7a) Colorimeters

The colorimeter uses the tristimulus measuring method where light that is reflected from the object is measured using three sensors filtered to have the same sensitivity, x (λ),y (λ),z (λ), as the human eye and thus measures the tristimulus values X, Y & Z, directly. The tristimulus values can then be converted to other colour spaces.

1.2.7b) Spectrophotometers

A spectrophotometer uses the spectrophotometric method of measuring colour and utilises multiple sensors to measure the spectral reflectance of the object at each wavelength or narrow wavelength range. The instrument's microcomputer then calculates the tristimulus values from spectral reflectance data by integration. Colour spaces can then be calculated from the tristimulus values. The spectrophotometer can also display a graph of the colour's spectral reflectance giving more detailed information about the nature of the colour. Colorimeters and spectrophotometers both have illuminant data stored in memory but tristimulus colorimeters generally measure only under C.I.E. Standard Illuminant C or C.I.E.

Standard Illuminant D65 which are very similar, whereas a spectrophotometer can calculate measurements under a variety of illuminants. It is for this reason that only spectrophotometers and not tristimulus colorimeters can be used to detect possible metamerism between samples.

These methods of colour measurement and control are used throughout industry around the world to standardise and communicate colour information in a scientific way.

1.3 Tooth Colour Determination and Prescription

In 1931 in the first scientific analysis of tooth colour 6000 teeth from 1000 patients were subjectively observed *in vivo,* (Clark, 1931a). The data collected was recorded using the then popular Munsell Colour System i.e. Hue, Chroma & Brilliance (now known as Value) (Munsell, 1926). Clark felt that the number of teeth examined was adequate to describe the extent of colour in the human dentition, and used the data to produce the first porcelain dental shade guide based on scientific data. From the data collected Clark determined that there were 703 colours that occurred naturally in the human dentition, and used this as the basis for the development of the Clark Tooth Color System which he advocated for use in shade determination and prescription for dental restorations (Clark, 1931b).

The Tooth Color System was organised to represent 342 gingival colours and 361 incisal colours, which could be generated from 13 different coloured porcelain powders. Clark felt that this number of colours, if used to form a dental shade guide, was too impractical for day-to-day use in the surgery, and so he developed the Tooth Color Indicator. The Tooth Color Indicator consisted of 60, tooth-shaped porcelain tabs, which enabled the clinician to determine the colour of the tooth, and write a prescription for any of the entire 703 colours in the system.

The "teeth" in the guide, are arranged in six rows of ten, with row 1 having the greatest amount of yellow and least amount of grey. Row 2 had a reduced amount of yellow and greater amounts of grey, and this change in colour continued to row 6, which had the least yellow and greatest amount of grey. Each one of the six rows is

arranged in ten gradations of light to dark, giving 60 shades which can be further modified, by the addition of red, green or blue modifiers in varying amounts, to give the total of 703 shades. A typical prescription using the guide would appear thus: RY23gin, where R would be the red modifier, Y2 the proportion of yellow/grey, 3 the intensity of lightness, and gin indicates that the shade refers to the gingival area of the tooth. In the Clark Tooth Color system the importance of assessing tooth colour under two different light sources (artificial and daylight) is stressed, as well as prescribing different shades for different areas of the teeth i.e. gingival, middle third and incisal. It is difficult to appreciate today what impact Clark's techniques had on shade selection in restorative dentistry in the 1930's. It is, however, certain that the comprehensive nature of Clark's study and recommendations was such that no significant research was undertaken in this field, (apart from Clark's own study on "Selection of Tooth Color for the Edentulous Patient" in 1947), Clark, (1947) until 1966, a lapse of over 30 years.

In 1966 Hayashi, (1967), examined 81 teeth in 68 Japanese patients in a study. He measured the colour of the teeth using carefully graded opaque coloured paper, and recorded the data using the Munsell Colour System of Hue, Chroma & Value (Hayashi, 1967).

From this data he developed a shade selection guide describing the colour space intervals he encountered in the study. He identified 125 colours and described a shade guide that had 25 colour tabs arranged on each of 5 Hue "pages" in 5 steps of Value, and 5 steps of Chroma. The study describes a systematic technique for shade selection, using four recommended steps.

(1) Determine the approximate Value of the tooth to be matched, (this reduces the number of tabs to be considered from 125 to 25).

(2) Determine the approximate Chroma of the tooth to be matched, (this reduces the number of tabs to be considered from 25 to 5).

(3) Determine from the 5 Hue tabs of the chosen Value & Chroma, the one that appears the closest match.

(4) If this tab does not appear to be as close as one would like, probe in three-dimensional colour space for a closer match. The next closest matches must lie in the vicinity of the initial choice, and probing is simply a matter of analysing Hue, Chroma & Value differences and moving in the appropriate direction.

Throughout the 20th century, manufacturers of dental restorative materials have produced their own individual shade guides, which represent the range of colours offered by their particular material.

One of the most widely used shade guides in restorative dentistry is the Vita Lumin Vacuum, (Vident, Baldwin Park, California), which consists of 16 tooth shaped porcelain tabs (Schwabacher and Goodkind, 1990). The manufacturer suggests that the tabs be arranged in one of two orders:

(a) Value i.e. lightest to darkest,

B1, A1, B2, D2, A2, C1, C2, D4, A3, D3, B3, A3.5, B4, C3, A4, C4

(b) Hue i.e. the tabs are grouped in four categories,

A1, A2, A3, A3.5 & A4 (Reddish Brown)

B1, B2, B3 & B4 (Reddish Yellow)

C1, C2, C3 & C4 (Greys)

D2, D3 & D4 (Reddish Grey)

The progression of 1 to 4 in each hue category is from lightest to darkest in value.

How the manufacturer came to select these 16 colours, as representative of the colours to be found in human dentition is not published. Research has shown that this shade guide is not representative of all the colours commonly found in natural teeth (Culpepper, 1970), (O'Brien *et al,* 1991). The porcelains manufactured by Vident, used to fabricate dental restorations at the time when this guide gained popularity, may have limited the range of colours represented. However, dentists throughout the world routinely use this guide, with some degree of success in matching dental restorations to the patient's existing dentition.

A survey of 115 dental schools throughout the world, into the incidence of colour related courses in dental education, revealed that only 3 schools devoted part of their curriculum to the subject (Sproull, 1967). Sproull also found that 79 of the schools recommended no method of colour selection, and that the most widely used method, adopted by 29 schools, was the use of commercially-supplied shade guides.

Culpepper investigated the ability of 37 dentists to match the shades of 6 natural teeth, using 4 different shade guides and 4 different light sources, under standardised viewing conditions (Culpepper, 1970). He concluded that none of the shade guides produced consistent results, the different light sources did not contribute to the accuracy of selection and individuals were not able to reproduce their selections from one session to another. He also concluded that critical colour perception varies from one individual to another and that the shade guides used did not represent the range of colours found in natural teeth. These findings led to the search for a method of objective measurement of tooth colour to eliminate the possibility of human error during colour analysis and to develop a shade guide which represented

the colours occurring in natural teeth.

Saleski, (1972), advised the application of industrial lighting standards during the determination and selection of tooth colour. He described the variables that influence colour perception as:

(a) Observer variables (no two people see colour in exactly the same way).

(b) Object variables (the influence of background colour, surface texture and simultaneous lightness contrast).

(c) Light source variables (objects may appear to be different colours under different lighting conditions).

To facilitate correct colour determination in the dental office, Saleski recommended that these variables should be recognised and controlled. To control lighting conditions, he advocated the use of an ideal light source that should have the following properties:

(a) Complete colour content.

(b) Sufficient intensity to overcome the ambient room light.

(c) Intensity of the light should be comfortable to the eye.

(d) The light should have a constant and unvarying colour temperature and spectral energy distribution under all conditions.

Sproull advocated the adoption and application of the Munsell Colour System in shade selection and prescription in dentistry (Sproull, 1973). In the first part of the paper Sproull discussed the principles of the three dimensional nature of colour as described by Munsell (Munsell, 1926). Sproull recommended the adoption of objective measurement of tooth colour using the science of colorimetry, as used in

industrial colour analysis, in dentistry. He also advocated spectrophotometric analysis of human teeth, in order to identify the colours of natural teeth to be represented in dental shade guides. Sproull stated that the requirements for any colour guide must include a logical arrangement in colour space, and an adequate distribution in colour space. He used a General Electric Recording Spectrophotometer to record the colours of 37 extracted teeth, and those of 2 manufacturer's shade guides, the Truebyte Bioform Shade Guide & the Vita Shade Guide. He concluded that:

(a) Existing shade guides do not extend through the volume of colour space required.

(b) An orderly or systematic arrangement or relationship between tabs is usually lacking.

(c) There will be clustering or duplication of colours in certain areas and voids in other regions.

In 1974 the J.M. Ney company commissioned Lemire & Burk with the task of attempting to overcome the long standing problems of shade selection and matching of natural tooth colours (Lemire and Burk, 1974). Their goal was to determine the distribution and frequency of natural tooth colours and develop a dental porcelain system capable of reproducing them. They also endeavoured to produce a shade guide that would enable easy and accurate communication of colour between clinicians selecting the shade, and the technicians who fabricate the restorations. The process of using such commercially-produced shade guides for colour selection is complicated by several factors as reported by Lemire and Burk, (1974), after comparison of 268 extracted natural teeth and two commercially produced shade

guides. They concluded that;

(a) There were variations regarding materials & chemistry between the guides and the restorative materials for which they are prescribed.

(b) There was a lack of coverage of the colours to be found in natural teeth.

(c) The shade guide samples were not presented in a visual colour order.

(d) The colours of the restorative materials represented by the guides were simply developed to produce a colour variety aesthetically pleasing to the human eye.

These findings were published in the book "Colour in Dentistry", which they advocated for use as a teaching aid in the application of colour science for the prescription of dental restorations.

Bergen and McCasland, (1977), investigated the effect of dental operatory lighting on tooth colour discrimination. In the first part of the study 41 dental personnel from the Walter Reed Army Medical Centre were asked to detect colour matches under natural daylight and 4 different operatory lights (Bergen and McCasland, 1977).

	Bulb	Colour Temp (Kelvin)	Tone
(a)	Verilux	6000^0	White
(b)	Verd-a-Ray crit Colour	5700^0	Green-Grey
(c)	Cool White	4200^0	Yellow
(d)	GE Chroma 75	7500^0	Blue

The natural daylight readings were used as the baseline and the readings from the four operatory lights subtracted from the baselines and recorded. Colour matches

were recorded under standardised viewing conditions, with only variables being the observers and the operatory lights.

Colour matches were made using the D&H Colour Rule (Bergen and McCasland, 1977). The D&H Colour Rule has two colour scales; the top scale is orange blending to blue and the bottom scale is violet that blends to green. Most observers can find a match between the two scales for most lighting conditions. A portion of both scales appears through an aperture in the rule; the scales are adjusted until the colours match. It was concluded that both the light source and the observer influence the selected match point, with the Verd-a-Ray crit Colour (a full spectrum bulb) giving the closest comparative matches to those recorded in daylight (Bergen and McCasland, 1977).

In the second part of the study 17 dental personnel from the Walter Reed Army Medical Centre were selected. They were asked to detect colour matches for 5 different tooth coloured samples from a standard set of 25 tooth coloured samples using the same four operatory lights as the first part of the study. All samples had a Value of 8.0 under the Munsell Colour Notation system and all colours were within the known range of the dental colour spectrum as described by Sproull, (1973).

The Verd-a-Ray crit Colour light (full spectrum light) gave the highest scores for colour matches of tooth coloured samples, and the Cool White operatory light (fluorescent light), the lowest scores. It was concluded that a full spectrum bulb offered viewing conditions closest to natural daylight of the four operatory lights tested.

Macentee and Lakowski, (1981), used two spectrophotometers, a Gamma Scientific 2400T telespectroradiometer and a Zeiss RFC3 abridged spectrophotometer, to

asses the suitability of these instruments for *in vitro* and *in vivo* colour measurement of human teeth. The instruments were found to have good agreement within themselves and with each other during repeated measurements of 3 Johnson Grey Tiles (H. & R. Johnson Ltd. Stoke-on-Trent, England), a commonly used industry colour standard. The researchers then measured the colour of 11 extracted teeth preserved in a buffered saliva substitute, and 17 dried teeth, with both instruments. The spectral reflectance curves of the teeth were recorded and the data plotted in C.I.E. Colour Space. All of the extracted teeth measured with both instruments shared common C.I.E. colour space with no significant difference in the colour ranges of the preserved or dried extracted teeth. To facilitate the colour measurement of teeth *in vivo*, a head support was fabricated for the patient, and a customised holder for the instrument, which enabled accurate positioning of the measuring device 1mm from the labial surface of the teeth. Spectrophotometric measurements were taken of 36 vital maxillary anterior teeth from 20 racially mixed male and female patients, with and without rubber dam masking the surrounding gingiva and paraoral tissues. This was the first time a spectrophotometer was used to record colour measurements of human teeth *in vivo* (Macentee and Lakowski, 1981).

The spectral curves were plotted and the data translated to C.I.E. Colour Space diagrams. The results showed significant differences between the teeth with surrounding rubber dam and those without, indicating that the colour of the teeth is affected by the surrounding mucosa. The range in C.I.E. Colour Space occupied by the natural teeth in this study showed less saturation compared with those in previous studies by:

(a) Lemire and Burk, (1974) using the General Electric Spectrophotometer

(b) Ishikawa, Ohsone and Sekine, (1969) using a colorimeter

(c) Tsuchiya, (1973) using a spectrophotometer and coloured photographs of teeth.

The natural teeth analysed *in vivo* in this study showed a greater saturation than the extracted teeth.

Macentee and Lakowski (1981), concluded that the comparison between instrumental colour measurements obtained from their study, and the other studies reviewed, showed a lack of overall agreement for colour space *loci* of vital and extracted human teeth.

The differences between the range of colours occupied by the extracted natural teeth and the vital teeth in Macentee and Lakowski's (1981) study and previous studies, may be accounted for by the technical difficulties encountered when measuring the colour of translucent, curved surfaces, and the difference in the instruments used for colour measurement (Goldstein and Schmitt, 1993).

Barna *et al*, (1981), investigated the influence of different light intensities on the visual perception and matching of tooth coloured samples. The investigators also studied the significance of colour defectiveness on the operator's colour perception. Fifty dentists from the National Naval Dental Centre, Bethesda, Maryland, USA, were screened for colour perception prior to participation in the study (Barna *et al.* 1981). Seven of the participants were found to have colour defective vision and this information was duly recorded. A room was constructed to standardise viewing conditions using full spectrum colour-corrected bulbs as the only illuminant light. The 50 subjects were asked to find matches for 5 tooth-coloured samples from a

selection of 25 tooth-coloured samples. The subjects performed this task under 4 different light intensities, i.e. 75 footcandles, (fc) 150fc, 225fc & 300fc. Barna *et al* found that the 43 (86%) subjects with normal vision scored an average of 44% correct colour matches. This compared to a score of 13% for the 7 (14%) subjects with colour defective vision; this was a statistically significant difference. The study showed no significant difference in the 50 subjects' colour match scores under the 4 different light intensities. Barna concluded that a possible explanation for this might be that once a certain light level is reached, colour matching can be performed adequately, and that above this level it does not influence the subject's ability to detect colour matches. Barna *et al* advised that in view of the influence of colour defective vision on the ability of the operator to detect colour matches, all prospective dental students and existing dentists should be screened for colour vision defects. They recommended that dentists with colour defective vision should obtain assistance when matching tooth shades.

Bangston and Goodkind, (1982), assessed the Chromascan, (Sterngoid Corp., Biodental Devices, Stamford, Conn.), a fibre optic tristimulus colorimeter, designed for *in vivo* colour measurement of teeth. The Chromascan employed an unfiltered tungsten-halogen light source passing through the fibre optic bundle to the sample surface. The light is reflected back through the probe tip and passes through three colour filters of red, green and blue. The data recorded from this instrument was in the form of R (red), G (green) & B (blue) designations. Bangston *et al* used the Chromascan to measure 194 dental porcelain fused to metal samples, of different shades and surface textures. They also measured 12 ceramic colour tiles (The British

Ceramic Research Association, National Physical Laboratory and the Society of Dyers and Colourists) of known colours to act as standards. The researchers investigated the possibility of using multiple regression equations to accurately convert the RGB designations, to C.I.E. X, Y, Z, Tristimulus values, the international standard for colour measurement.

A General Electric Recording Spectrophotometer, (General Electric Co., West Lynn, MA, USA), was used to measure the same samples to obtain the C.I.E. Tristimulus values, which were used as the standard to compare the Chromascan calculations. The coefficients of variation were 1.4%, 1.4% & 1.3% for the prediction X, Y, & Z respectively from the R, G, & B designations.

Bangston and Goodkind (1981), concluded that the Chromascan could reproduce R, G, B designations with reasonable accuracy and that in conjunction with multiple regression equations it was valid to predict estimated C.I.E. X, Y, & Z Tristimulus values. The researchers also concluded that because of the poor repeatability of the Chromascan data as compared with the Recording Spectrophotometer and its inability to measure surface texture, that further investigation was necessary before the Chromascan could be accepted as a reliable instrument for research or clinical dentistry.

Goodkind *et al* (1985) used the Chromascan to measure 100 extracted human teeth from various ethnic groups, with clinical crowns free of restorations, from the following range of locations (Goodkind *et al*, 1985):

38 from 15 males

62 from 23 females

14 maxillary incisors

20 maxillary posteriors

48 mandibular incisors

18 mandibular posteriors

The teeth were scaled and pumiced then stored in a solution of 9% Sodium Chloride & Thymol. The specimens were kept moist during measurements and placement of the teeth relative to the Chromascan was accomplished with a custom matte black holder.

Each tooth was measured with the 2mm probe tip at the cervical, middle and incisal regions, and the R, G, B readings recorded. The specimens were measured at the same sites with a General Electric Recording Spectrophotometer, (General Electric Co., West Lynn, MA, USA), and the C.I.E. X, Y, & Z Tristimulus values calculated. Multiple regression equations were used to convert the R, G, & B designations to C.I.E. X, Y, & Z Tristimulus values. Goodkind *et al* (1985) also devised a protocol to determine which of the two methods of colour measurement agreed more closely with human observation. Three trained colour observers were presented with 2 groups of 50 reference teeth under standardised lighting conditions. The first group contained specimens measured with the Chromascan and the second group with the Recording Spectrophotometer. Each group contained 25 teeth and their nearest colour match as perceived by each instrument. The observers were asked to choose the nearest colour match to each reference tooth without knowledge of which instrument was used for the measurements. The colour matches selected by the human observers were compared to the instrumental closest matches. The observers selected the tooth specified by the spectrophotometer as the better match for 27 of

the reference teeth, and that indicated by the Chromascan for 23 of the teeth. Goodkind *et al* (1985) concluded that;

(a) Human observers are almost as likely to agree with the Chromascan as with the spectrophotometer in regard to what pairs of teeth look like.

(b) The instruments detected increases of R, G, & B and X, Y, & Z form the incisal through to the cervical third of the teeth.

(c) The coefficients of variation for the prediction X, Y, & Z respectively from the Chromascan ranged form were 6.6% to 11.4%.

(d) The decrease in accuracy of the measurement of the colour of natural teeth form that of flat porcelain samples was probably due to the complex structure of teeth.

(e) Further studies were necessary to determine if the Chromascan can be used to measure the colour of natural teeth.

In 1985 Moser *et al* conducted a study of 670 dentists from the United States of America, in which the vision of the participants was tested for red-green colour deficiency. The investigators used the Dvorine Pseudo-Isochromatic Plate Test to test the visual acuity of the subjects of which 94% were male and 6% female, (a representative cross section of the profession at the time), (Dvorine, 1953). They found that 9.9% of the dental professionals tested had some degree of red-green colour defective vision, which would affect their visual perception of tooth coloured shades. The investigators concluded that all dentists and dental students should be tested for red-green colour deficiency (Moser *et al.* 1985).

Van Der Burgt *et al* (1985) presented a new method for matching tooth colours with colour standards. The specimens consisted of 10 extracted human maxillary incisor teeth which had their pulps extirpated and the pulp chambers cleansed to prevent discolouration. The colour standards consisted of colour cartons (Sikkens Colour Collection 20/21, Sikkens, Sassenheim, The Netherlands) arranged according to the three visual colour dimensions Hue, Value & Chroma of the Munsell system. The colours of the colour standards were measured using a spectrophotometer (Hunterlab Spectrophotometer D54P-5, Hunter Associate Laboratory Inc, Reston VA, USA) and the data expressed in Munsell notation of Hue, Value and Chroma. Twenty-five observers were selected from a group of dentists and dental students whose colour vision was found to be normal as for the Farnsworth-Munsell 100 Hue Test (Farnsworth, 1957). Viewing was carried out under standardised background and environmental conditions and the samples were illuminated with daylight colour corrected fluorescent tubes. The specimens were observed using a custom holder of a neutral grey material, with two circular apertures of 4mm diameter, 6mm apart. The upper aperture was placed over the mid-cervical part of the tooth and the colour standard carton behind the lower aperture. Two viewing methods were employed, in method one the holder was held 30mm from the labial surface of the tooth and in method two the holder was placed directly on the tooth surface. The observers were asked to select the nearest colour match with the tooth and the colour standards for each of the 10 teeth on two separate occasions. The colour standard selected in each instance was then designated to be the colour of the mid-cervical of the tooth. The results showed statistically significant differences in the perceived colours of the 10 teeth. In method one there were no significant differences within

observers and the differences between observers contributed only to a very small extent to the total variance. The average scores (+/- standard deviation) of the first and second examination for Hue, Value & Chroma of 10 teeth, displayed almost 100% inter-examiner agreement between the 25 examiners. Observers expressed difficulty obtaining a match using method two, with the standard deviation of the mean values for Hue, Value & Chroma scores reflecting this observation with values about three times larger than that of method one. van der Burgt *et al* (1985) theorised that the aperture placement in method one allowed complete illumination of the tooth by ambient light, with the light reflected from the tooth surface observed through the 4mm hole. This could be considered as large window illumination and small window collection, which allows proper inclusion of internal diffusion of light on the tooth and a proper value of volume reflection. In method two the same window is used for illumination and observation of the reflected light. The diameter of the window is too small compared with the distance the light travels in the course of the internal diffusion to give a proper value of volume reflection. The researchers concluded that visual and instrumental colour determinations on teeth that use the same window of illumination and observation will be subject to large errors, (van der Burgt *et al.* 1985).

The Chromascan fibre optic tristimulus colorimeter was used to measure the colour of 2830 human teeth *in vivo,* (Goodkind and Schwabacher, 1987). The teeth of 500 individuals were measured during the experiment, and the sex, hair and eye colour, birthplace, age group and tooth position of each person were recorded. The probe tip of the Chromascan was positioned on the labial surface of the teeth with the aid

of a custom holder. The teeth selected for colour measurement were the 13,12 & 11 in the maxillary arch and the 31,32 & 33 in the mandibular arch, with the crowns of the teeth selected, being free of coronal restorations. Three sites on the labial surface of each tooth were measured i.e. the cervical, middle and incisal regions. A preliminary study where 2 operators independently measured 60 teeth of 10 different individuals showed no statistically significant difference between operators in measuring tooth colour. The interoperator reproducibility of the measurements repeated on the same 10 patients showed no statistically significant differences between the two replications. Goodkind and Schwabacher, (1987), used the multiple regression equation reported by Bangston and Goodkind, (1982) to convert the R, G, & B designations to C.I.E. X, Y, & Z Tristimulus values and subsequently used the Davidson interpolation program (Davidson Colleagues, Tatamy P.A.), to convert the data to Munsell notation of Hue, Value & Chroma. From these colour measurements the researchers concluded that:

(a) Teeth do not have a single uniform colour

(b) The middle site appears to represent tooth colour best (the cervical and incisal sites seem to be more affected by their surroundings).

(c) Women on average have lighter, less saturated and less reddish teeth.

(d) Teeth tend to become darker and more reddish with advancing age.

(e) Canine teeth are darker than incisors and the central incisors have the highest Values found in all sites.

Johnston and Kao, (1989), assessed tooth colour matching for composite resin

veneers by two scales of visual criteria, and by instrumental colorimetry. The United States Public Health Services, (USPHS), method advocates a visual comparison of the restoration and the adjacent tooth and assigning a score of:

(a) Alpha (for a perfect match)

(b) Bravo (for a mismatch)

(c) Charlie (for a mismatch outside the normal range of tooth colour, shade or translucency)

The second visual criteria assessed was an expanded visual rating scale for appearance match (EVRSAM) which suggested an extended rating score of:

(a) 0 Excellent aesthetic match, an exact match or one so close that the restoration can only be delineated with difficulty.

(b) 2 Very slight mismatch with aesthetics still good to very good.

(c) 4 Obvious mismatch but within an acceptable range for most patients.

(d) 6 Poor aesthetics on the borderline of unacceptability.

(e) 8 Very poor aesthetics that would be acceptable for nearly all patients.

(f) 10 Totally unacceptable aesthetics.

A colorimeter (Chroma Meter CR-21, Minolta Corp., Industrial Meter Div., Ramsey, NJ) was used to measure the colour of the mid facial area of the restoration and the adjacent teeth. The colour parameters were recorded in C.I.E. Tristimulus

values (L* a* b*) and C.I.E. Colour Differences (ΔE) calculated for the differences between the teeth and the restorations. Johnston and Kao, (1989), assessed and measured the colour of 42 composite resin veneer restorations, placed in patients for aesthetic reasons, using one of three different resins.

(a) Durafill (Kulzer & Co. GmbH, Bereich Dental, Wehrheim, Germany)

(b) Prisma Micro Fine (L.D. Caulk Co. Milford, DE, USA)

(c) Silux (3M, St Paul, MN, USA)

Two examiners, using the USPHS and EVRSAM criteria, one week after placement of the restorations performed a baseline colour evaluation. Three colorimetric measurements of the mid facial points of the teeth and the restorations were also taken at this visit and the average colour difference C.I.E. (ΔE) calculated. The patients were recalled at three-month and twelve-month intervals and the subjective and instrumental colour measurements were performed again. The results of the three methods were recorded and statistical analysis showed that there were statistically significant relationships between the instrumentally derived colour differences and the visual rating scales. The researchers found no significant improvement in colour evaluation and description with a lesser degree of error using the EVRSAM criteria rather than the USPHS criteria. Johnston and Kao, (1998), concluded that a tristimulus colorimeter gives a consistent colour evaluation of teeth. In contrast to human observations made under laboratory conditions where a C.I.E. colour difference (ΔE) of 1 was detectable, the average colour difference between

the composite resin veneers and adjacent teeth rated as a match in the oral environment in this study was 3.7. The researchers concluded that during human observation of colour matches of teeth and restorations in the oral environment, factors other than the three dimensions of colour, such as translucency, tooth structure and surface texture, are taken into account by the eye.

Schwabacher and Goodkind (1990) performed colour analysis of three dental porcelain shade guides and compared them with the colours of 2830 natural teeth measured *in vivo* in a previous study by Goodkind and Schwabacher (1987). A Diano Match-Scan II (Milton Roy Co., Diano Colour Products, Rochester, NY, USA) spectrophotometer was used to measure the colour of the three guides listed below;

(a) Vita Lumin Vacuum Shade Guide (Vita Zahnfabrik, Bad Sackingen, Germany)

(b) Trubyte Bioform Colour Ordered Shade Guide (Dentsply International Inc., York, PA, USA)

(c) A surviving porcelain shade guide of E.B. Clark (Clark, 1931b), (Clark, 1931a) & (Clark, 1933).

The middle third of each of the shade guide tabs was measured spectrophotometrically and the spectral reflectance recorded for C.I.E. Illuminant C, and C.I.E. 1931 Standard Observer of 2^0. The spectral reflectance curves were converted to tristimulus values, which were subsequently converted to Munsell values of Hue, Chroma & Value. The colours represented by the shade guides were compared to the measured colours of the 2380 natural teeth and the following

conclusions were drawn;

(a) The shade guides studied did not match the colour space of vital teeth at the middle facial third. The darker, redder teeth were not matched by the shade guide porcelains, neither were lighter, yellow, and more saturated teeth.

(b) Current dental porcelains are too yellow with respect to patient's teeth. Deficiencies were noted in Hues in the yellow-red range to 8 YR, and in values to approximately 8.

(c) The flounder-like configuration of the points representing teeth *in vivo* in the colour space suggested that a representative shade guide could be assembled similar in number to current guides because Hue, Value and Chroma are not independent.

Research by Donahue *et al,* (1991), into shade colour discrimination by men and women set out to investigate the traditional belief that women were more capable of matching colours than men (Donahue *et al.* 1991). Donahue *et al* selected twelve dental students, six men and six women, between the ages of 24 to 35 years of age. To rule out any defective colour vision, these students were given the Farnsworth–Munsell 100 Hue Test. This test separates persons with normal colour vision into superior, average and low colour vision, and also the Farnsworth Panel D-15 test, which detects observers with moderate and severe loss of chromatic discrimination (Farnsworth, 1957). None of the twelve participants had any of these colour aberrations. The twelve participants acted as both examiners and subject during this trial and all examiners were instructed in the fundamental principals of Munsell variables of Hue, Chroma and Value and in shade selection. The subject's teeth

selected for colour matching were the maxillary right central and lateral incisors and canines. The shades of the incisal third and gingival third of each tooth were determined. Three shade guides were used in this study:

(a) Vita Lumin Vacuum (Vident, Baldwin Park, CA, USA)

(b) Crystar Porcelain (Unitek Corporation, Monrovia, CA, USA)

(c) Bioform (Dentsply Int., York, PA, USA)

The examiners determined colour matching under three different light sources:

(a) North Daylight (Sun)

(b) Lumin Shade Light (H-H-Jahnn, Hamburg, Germany)

(c) Philips-Westinghouse Ultrahume (Westinghouse, Minneapolis, MN, USA)

All students measured 66 individual dental sites including their own teeth and rotated observations through the three illuminants with the three guides.

Following statistical analysis of the results the researchers concluded that

(a) Women do not agree with one another more than men in shade selection.

(b) Women agreed with one another best when using the Lumin light source.

(c) No statistically significant difference was found in agreement among men with respect to the three light sources and two shade guides. (No particular light source and shade guide improved agreement for men.)

(d) On average 63% of the men and 58% the women agreed on a choice of Value index. The difference is small and only slightly significant.

The researchers concluded that the clinical implications of these findings were that there is no reason to select clinicians during shade selection according to gender. Clinicians should be screened for colour-vision defects, and that there is not much

hope for universal agreement as to the best colour match even under similar illumination.

Wasson and Schuman, (1992), examined 150 subjects, 75 men and 75 women, from a sample population, which consisted of dental students, dentists, dental hygienists, dental technologists and dental assistants, for possible colour-vision defects. The Standard Pseudoisochromatic Plates-Congenital (SPP-C), Part One- Congenital Colour Vision Defects, was used to detect hereditary colour-vision defects, (Klingaman, 1990). This test is used to screen colour normals from individuals with any hereditary red-green defects (mild, moderate and severe). Each subject viewed 19 colour plates, which consisted of patterns of colour dots of a uniform size. The results corroborated previous studies in that they showed that colour-vision defect is exclusively a male problem. Seven (9.3%) of the 75 male participants in this study tested positive with no females proving positive, which mirrors male and female relationships as they exist in the general population. This researcher advocated that all male dental personnel should be tested for colour-vision defects and if found positive should seek assistance from other members of the dental team and/or colorimetric devices during shade determination.

Goldstein and Schmitt, (1993), assessed the repeatability of specially designed intraoral colorimeter in determining tooth colour (Goldstein and Schmitt, 1993). A Minolta CS-100 colorimeter (Minolta Corp. Industrial Meter Division, Ramsey, NJ, USA), with a DP-101 data processor was adapted for intraoral use. To test the repeatability of the instrument five different shades of Trubyte Bioform, (Dentsply

International, York, PA, USA), porcelain denture teeth, and five different shades of Trubyte Bioblend, (Dentsply, International, York, Penn.), acrylic resin denture teeth, were mounted in a fixed position in front of the fixed mounted colorimeter. The middle third of each of the denture teeth was measured three times and readings recorded in C.I.E. L*a*b* notation. The measurements were repeated after three days without recalibration of the instrument and after eight days following recalibration. *In vivo* measurements were taken of the central maxillary right incisor of five patients over the same time period. The unit was hand held and three readings were taken in each of the incisal, middle and gingival thirds of the mesiodistal middle third of the teeth. The data recorded was used to calculate the C.I.E. ΔE colour differences over the time periods for the measurements of the same denture teeth and teeth. The ΔE colour differences ranged from 0.57 to 2.75 for the denture teeth, and from 1.1 to 32.1 for the *in vivo* measurements of the central incisors. The researchers concluded that the specially modified colorimeter was ineffective in producing repeatable readings of tooth colour. The unit was bulky and difficult to position when hand held for *in vivo* work. When mounted in a fixed position and recalibrated before each use, it was unreliable and sensitive to changes in the fibreoptic cord, ambient light and room temperature.

Douglas, (1997), assessed the precision and repeatability of the Minolta CR-321 tristimulus photoelectric colorimeter, (Minolta Corp. Ramsey N.J, USA), combined with a custom intraoral positioning device, during *in vivo* measurement of tooth colour. The researchers investigated the intra-examiner and inter-examiner

repeatability of the instrument when used for longitudinal assessment of tooth colour. The Minolta CR-321 colorimeter uses an internal circumferential 45^0 illumination and 0^0 viewing angle geometry to measure an area 3mm in diameter. The vestibular centre of the maxillary left central of seven subjects was measured *in vivo*. To facilitate these measurements, alginate impressions of the subjects' maxillary arches were taken and dental stone models were cast from them. A polyvinylsiloxane impression was taken of the colorimeter measuring head and a replica model cast in dental stone. The replica head was attached to the vertical arm of a surveyor table and the subject's maxillary model fixed to the table with the labial uppermost. The replica head was positioned flush with the centre of the maxillary left central labially on the model and a custom positioning jig fabricated in specially formulated white polyvinylsiloxane putty, (Clinical Research Dental, London, Ontario, Canada) for each of the seven subjects. A 3mm-diameter window, corresponding to the centre of the maxillary left central labially was cut in the positioning jig to facilitate accurate positioning of the measuring head. The colorimeter measuring head was placed in the jig and introduced to the surface of the subject's tooth, and colour analysis recorded in C.I.E. L*a*b* coordinates relative to Standard Illuminant D65 and C.I.E.1931 standard observer functions. This procedure was repeated nine more times for each tooth to give a total of ten measurements per tooth. Examiner 1, who had three years experience in clinical and laboratory colorimetric assessment of dental restorations, carried out the measurements. These procedures were carried out again at 14 & 28 days. On day 28, inter-examiner reliability was tested between examiner 1 and two additional examiners, examiner 2 for subjects 1 to 3, and examiner 3 for subjects 4 to 7.

Examiners 2 and 3 had no previous experience with tristimulus colorimeters. The data recorded was used to calculate the C.I.E. ΔE colour differences over the three periods, and an overall inter-examiner repeatability colour difference was calculated. It was concluded that:

(a) The Minolta CR-321 colorimeter equipped with a custom positioning jig can be used for intraoral measurement of longitudinal changes in tooth colour.

(b) The *in vivo* colorimetric measurements of incisor tooth colour are reliable, sensitive to changes in colour >0.34 ΔE units at a confidence level of 95%.

(c) Untrained observers can be readily trained for colorimetric assessments of maxillary central incisor teeth with reliability similar to that of an experienced examiner.

(d) When there is more than one examiner, differential measurements of teeth should be made by the same examiner to avoid variability caused by differences in interexaminer accuracy.

The Minolta CR-321 colorimeter was used once again to examine the acceptability of shade differences in metal-ceramic crowns by Douglas and Brewer, (1998). The same technique, was used as Douglas (1997), where a custom-positioning jig was used for accurate placement of the measuring head, during the colour measurement of 60 commercially fabricated metal ceramic crowns of prescribed Vita shade A3.5. Mean C.I.E. L*a*b* values were determined after three separate measurements of each of the 60 crowns in succession. ΔE colour differences of all possible pairings of the 60 crowns were calculated, and analysis of the C.I.E. L*a*b* coordinates carried

out to separate the crowns into three groups of ten pairs with the following criteria:

(a) L* group where pairs differed mainly in Lightness

(b) a* group where pairs differed mainly in Redness

(c) b* group where pairs differed mainly in Yellowness

The crown pairs were selected to represent a variety of ΔE values within the range of colour differences.

Twenty prosthodontists, (16 men and 4 women) were selected for visual evaluation of the crown pairs. The observers were screened for colour-vision defects, and all visual assessments were made under controlled lighting conditions. The observers were asked to focus their attention on the centre of the crown and answer the following questions regarding the shade in the midlabial aspect of each pair.

(a) Do you detect a colour difference between the two crowns? (Perceptibility).

(b) Would you accept or reject the shade match under clinical conditions? (Acceptability).

From the analysis of the results the researchers concluded that:

(a) Correlations between instrumentally derived colour differences (ΔE) and visual assessments of perceptibility and acceptability of small colour differences in metal ceramic crowns were co-ordinate-dependent. Correlations were strong for crowns differing in yellow chroma and crowns differing in red chroma but weak for crowns differing in lightness.

(b) Thresholds for acceptability were significantly lower for metal ceramic crowns

differing in their red chroma (mean 1.1 ΔE units) as compared with crowns differing in their yellow chroma (2.1 ΔE units)($p<0.05$).

(c) Thresholds of perceptibility (mean 0.4 ΔE units) were significantly lower than thresholds for acceptability (1.7 ΔE units) for metal ceramic crowns differing in their chroma ($p<0.05$).

In 1998 the dental company Shofu, (Shofu Inc. Kyoto, Japan), introduced a computer colour matching system called the Vintage Halo Computer Colour Search System. The system uses a hand held M-1863d colorimeter, (Shofu Inc. Kyoto, Japan), connected to a dedicated computer and printer. The measuring head of the colorimeter is held at the cervical third of the patient's teeth adjacent to the tooth to be restored to discern the required shade for the prescription. Having measured the colour of the adjacent teeth, the data held in the computer's memory bank enables a prescription to be generated in terms of Vita Lumin Vacuum Shades, (Vita Zahnfabrik, Bad Sackingen, Germany). In addition to the shade required to fabricate the restoration, a prescription detailing the specific amounts of opaque, body and enamel shades of Shofu Vintage Halo Porcelain (Shofu Inc. Kyoto, Japan), required to replicate the tooth can be generated (Yamamoto, 1998).

1.4 Porcelain Laminate Veneers

1.4.1 Development of Porcelain Laminate Veneers

In the late 1920's, with the advent of talking motion pictures, Dr Charles Pincus, a Beverly Hills dental practitioner, became aware of the film industry's demands on stars and starlets of the day to have a glamorous smile. Many of Dr.Pincus' patients were in the movie business and so he began experimenting with various methods of improving their less than perfect smiles to match the expectations of the audiences. The dental work had to look good for close up camera work and be able to be tolerated for long periods without interfering with speech. As aesthetics were the only consideration for these restorations he developed porcelain facings which met these conditions. Pincus fired a thin layer of porcelain onto platinum foil and designed the appliance so that it would not interfere with oral function or speech (Pincus, 1938). The actors would only wear the appliances during performances as they could not eat with the appliances *in situ* because they were not permanently fixed to the teeth, but simply held in position by denture powder.

This limitation to the function of such aesthetic appliances was partially removed in 1955 with the discovery of bonding. A method was devised of bonding dental acrylic resin to tooth surface to give an aesthetically pleasing restoration by Buonocore, (1955). He found that the application of a weak acid to the surface of enamel resulted in an irregular and pitted surface. He then used this surface to create micro-mechanical attachment between the material and the tooth. Unfortunately this method was ultimately unsuccessful because of the unpleasant taste of the residual

monomer released from the resin and the staining and mouth odour retained by the acrylic.

It was not until the early 1970's that any further developments were made in bonding with an innovative combination of acid-etched bonding of enamel to porcelain to restore a fractured incisor developed by Rochette (Rochette, 1975). This procedure was successful with clinical results reported over a three-year period, but it seems now that the technique was ahead of its time as nothing more was heard of this method for many years.

The emphasis in bonding of aesthetic materials was directed towards the improvement of plastic dental materials bonded directly to etched enamel. There were advances in the aesthetics of the materials used in these procedures, as acrylics were superseded by unfilled resins, filled and macrofilled resin-based materials, but none of these could create a truly permanent aesthetic restoration.

A preformed factory processed Mastique plastic laminate (Caulk-Dentsply, Milford, DE, USA) was developed in the 1970's, to improve tooth colour without resorting to full crown preparation (Faunce, 1976, 1977). The technique involved the selection of the closest match to the patient's teeth from the variety of preformed shapes, and modifying them at the chairside to give a fairly close adaptation. The laminate was then bonded to the etched tooth surface with composite bonding agents of various shades. The adaptation of the laminates was time consuming for the clinician and the fit was generally unsatisfactory. To alleviate this part of the problem dental laboratories started using a heat forming method of adapting the Mastique system. This did help for a while, but the main problem was the inadequate bond between the laminate and the composite-bonding agent. Because of

the stresses transferred to the laminate by the occlusal forces it was not uncommon for the whole laminate to debond from the tooth or composite, this combined with edge chipping and marginal percolation resulted in failure (Boyer, 1982). This resulted in differential staining of the composite and laminate, exposure of the initial discolouration leading to an unaesthetic restoration and cosmetic failure for the patient, which lead to the search for different solution to the problem.

1.4.2 Development of Enamel Bonding

In 1983 the technique of acid etching and pre-treatment of enamel with a coupling agent was combined with porcelain laminate veneer restorations (Calamia, 1983), (Horn, 1983a), (Horn, 1983b). The enamel was acid etched with 30-50% ortho-phosphoric acid for 60 seconds, which resulted in a micromechanically retentive surface 25-50 μm deep (Jordan, 1993). The difference in resistance to acid attack between the enamel prisms and the interprismatic enamel results in a rough pitted surface creating a hundred-fold increase in the surface available for bonding (Sebor, 1983). The fit surface of the porcelain laminate veneer was acid etched in the laboratory with 10% hydrofluoric acid for 4 minutes to give a micromechanically retentive surface on the restoration. The etched surface of the porcelain was then treated with the coupling agent silane, which consisted of either gamma-methacryloxipropyltrimethoxysilane or
gamma-glycidoxypropyltrimethoxysilane, before being bonded into place. This allowed the porcelain to bond to the composite resin (McLaughlin, 1984). It was

discovered that when a coupling agent consisting of phosphate esters of Bis-GMA were applied to the enamel surface, increases in bond strengths of up to 86% of composite to the enamel were possible (Chalkley and Jensen, 1984). This combination of chemical and mechanical bonding was termed "enamel fusion" (Chalkley and Jensen, 1984), and still forms the basis for modern day bonding of porcelain laminate veneers.

1.4.3 Clinical Indications for Porcelain Veneers

There are many indications for porcelain laminate veneers, which may include (Freedman and McLaughlin, 1990):

(a) Stained or darkened teeth

(b) Hypocalcification

(c) Diastemas

(d) Peg laterals

(e) Chipped teeth

(f) Rotated teeth

(g) Lingually malpositioned teeth

(h) Stained restorations

(i) Foreshortened teeth

(j) Malpositioned midlines

(k) Toothbrush abrasion

(l) Missing lateral incisors

1.4.4 Clinical Procedure for Porcelain Laminate Veneers

Having determined that a porcelain laminate veneer is the restoration of choice, the operator may then begin preparation of the patient's teeth. It may be preferable to take the shade of the patient's adjacent teeth before commencing reduction of the tooth, as the adjacent teeth will change colour during the preparation time as they lose moisture and become desiccated.

There are several variations of veneer preparation design, but all should adhere to some basic considerations (Freedman and McLaughlin, 1990):

(a) The preparation should be as conservative as possible.

(b) It should allow for a covering of approximately 0.5mm of porcelain without giving the tooth an overly thick appearance.

(c) It should not penetrate into dentine if at all possible, especially at the borders of the preparation where leakage is most likely.

(d) It should allow for a cleansable gingival margin.

(e) It should not include any sharp internal angles, especially at the incisal edge where stresses will be the greatest.

(f) It should allow for a path of insertion of the veneer, which is free from undercuts.

(g) Enough clearance must be present interproximally to allow for a separating strip to be placed between the adjacent teeth during bonding.

(h) Any area of the tooth, which is visually accessible, should be covered by porcelain.

Combinations of coarse and fine diamond burs are used to remove 0.5mm of enamel from the labial aspect of the tooth. This preparation is extended mesially and distally to the interproximal areas and is finished as a chamfer margin. The preparation is continued towards the cervical and finished as a supra-gingival chamfer margin. This procedure allows the placement of a 0.5mm porcelain laminate veneer without alteration to the labial profile of the tooth, and also facilitates the accurate positioning of the veneer. The preparation may be extended onto and or over the incisal edge of the tooth depending on the constrictions of the patient's lateral and or protrusive excursive movements. The preparation should not extend past the contact points mesially and distally, as temporisation is not generally carried out and this would lead to closure of the mesio-distal space over the interim period, and the veneer will not fit. The entire preparation should be totally free of undercut.

Following preparation of the teeth a polyvinylsiloxane master impression is taken of the prepared teeth, together with an impression of the opposing arch and relevant occlusal records. Upon receiving the porcelain laminates from the laboratory the veneers are tried on the teeth and checked for marginal fit, contact areas, occlusion and aesthetics. If multiple veneers are being fitted they must be tried in simultaneously, prior to bonding, to check mesial and distal contacts are harmonious and do not interfere with accurate placement of the veneers. Trial insertion of the laminate veneers generally requires the use of a try-in medium to hold them *in situ,* as they have little frictional retention because of the nature of the preparation. This may be water, glycerine or a try-in paste. The other main advantage of using a try-in medium is that a better realisation of the combined shade of the tooth and veneer can be discerned because the light refractive index of the liquid medium is closer to that

of the porcelain than air. Having checked the fit of the veneers the bonding procedure can be commenced. Any remnants of the laboratory etch procedure and or try-in medium is removed from the surface of the laminate by acid etching with 37% orthophosphoric acid, for one minute, and then washing thoroughly with water. A silane-coupling agent, is applied to the fit surface of the veneer and left for one minute. It is then rinsed off with water and gently air-dried. Isolation and moisture control measures such as rubber-dam application are taken to ensure no contamination of the tooth surfaces, or harm to the patient's oral tissues. The teeth to be veneered are cleaned with pumice and rinsed and isolated from the adjacent teeth with separating strips. The teeth are then etched with a 37% orthophosphoric acid, for 30 seconds, washed and thoroughly air-dried. One drop of activator and one drop of resin of the bonding medium per veneer is mixed for ten seconds. This is then applied in a very thin layer to both the tooth and the bonding surface of the veneer. The correct shade of luting cement is applied to fill the bonding surface of the veneer and gentle pressure used to place the veneer in the correct position on the tooth. The aesthetics of the veneer can now be examined and if shade modification is required the veneer can be removed and cleaned with a solvent. Composite shade modifiers may be used on the fit surface of the veneer to modify the shade of the restoration until an aesthetic result for the operator and patient is achieved. Once the shade and placement of the veneer is satisfactory the composite resin can be light cured with a suitable light curing unit. The light curing wand is held to the incisal edge and activated for five seconds. This is sufficient to hold the veneer securely in position during removal of the excess composite from the gingival, proximal and lingual edges with a scaler or similar instrument while the composite is still in a

plastic state. After removal of the flash, light curing on the labial surface for 40 seconds, followed by light curing from an inciso-lingual direction should complete the initial setting of the composite. Removal of any excess composite from the edges of the restoration is completed with fine diamond burs and composite finishing strips. The margins of the restoration are then polished with impregnated silicone discs to ensure a smooth junction between the restoration and the tooth that should enable the patient to maintain a healthy periodontal condition around the porcelain laminate veneer. The patient is then given instructions on the post-operative care and maintenance of the laminate restorations and given a further appointment for a check on the aesthetic result and gingival response.

1.5 History and Development of Dental Porcelain

Porcelain was first used in dentistry in the eighteenth century when Alexis Duchateau, a French apothecary, used a porcelain paste to produce complete dentures. The early dentures produced with this technique were ill fitting because of the uncontrolled firing contraction. Duchateau sought the advice of the dentist Dubois de Chemant to help overcome the problem of shrinkage, and de Chemant subsequently manufactured complete dentures using porcelain paste supplied by the Wedgwood porcelain factory in 1792. In 1808 Guiseppangelo Fonzi produced the first individual porcelain denture teeth, which because of their brittleness and unaesthetic opacity, did not have any critical acclaim. The first commercially successful technique in the production of porcelain teeth came in the 1850's when Samuel Stockton, S. S. White and Claudius Ash manufactured porcelain denture teeth incorporating mechanical retention, which were utilised in the fabrication of vulcanite dentures.

Porcelain was not used for fixed prosthodontics until 1889 when Dr Charles Land filed the first patent for a porcelain jacket crown using feldspathic porcelain combined with a platinum foil matrix firing technique. This technique was refined in 1903 by Dr E. B. Spaulding, with the incorporation of a shoulder preparation, and in 1908, Dr A. E. Schneider advocated that the shoulder should be prepared at 90^0 to the occlusal force. By 1925, when Dr Albert Le Gro published "Ceramics in Dentistry", high fusing dental porcelains were a widely established, highly aesthetic restoration. However the main disadvantage of porcelain as a restorative material was its brittleness and it was prone to fracture under loading. Various attempts were

made to reinforce the porcelain with metals such as iridioplatinum, but while these were largely unsuccessful at the time, they laid the groundwork for the general principal of porcelain fused to metal as a method of reinforcement. In 1962 M. Weinstein and A. B. Weinstein filed the first patent in the USA for the bonding of porcelain to gold alloys, which lead to the real possibility of metal fused to ceramic crowns as a restorative technique. McLean and Hughes developed the alumina-reinforced porcelain jacket crown in 1963, and McLean and Sced introduced the platinum foil bonded reinforced crown in 1976, where a layer of tin oxide was deposited onto the platinum foil and the porcelain fused to the tin oxide layer. During this period of development in porcelain restorative techniques Vines, Semmelman, Lee and Fonveille introduced vacuum firing of the porcelain in 1949, which lead to denser, stronger and more translucent restorations, (Kelly *et al,* 1996). Research and development of all porcelain and metal bonded to porcelain restorations is evolving continuously with many different systems, such as castable glasses, pressed glasses, milled ceramics and technical ceramics available. These are capable of producing strong, highly aesthetic restorations.

1.6 The Nature of Dental Porcelain

Dental porcelains are categorised by their fusing temperature and are divided into three separate groups:

High Fusing	1288^0 to 1371^0C
Medium Fusing	1093^0 to 1260^0C
Low Fusing	800^0 to 1050^0C

All dental porcelains are based on the silicon-oxygen glass-forming network.

Most of the modern dental porcelains are low fusing and are not true porcelains at all, in that they do not exhibit the crystalline structure of metals and other solids, but are more akin in nature to glasses. Glasses have a non-crystalline, composite structure with a vitreous matrix, which incorporates various crystalline phases.

Glasses have an amorphous structure with typical physical properties that include brittleness and lack of a definite melting point. The dental porcelains used to fabricate metal bonded to ceramic crowns, and also veneers and inlays using the refractory method, are based on feldspathic porcelains. Silica (SiO_2) is the main constituent of feldspathic porcelain, and is found in feldspar which occurs naturally throughout the world in the form of clay and is basically an aluminosilicate compound. Dental porcelains use a silicone-oxygen network as the glass-forming matrix in the form of the SiO_4 lattice. The feldspars also have different amounts of metallic oxides incorporated in them dependent on their origin, but there are only two types used in dental porcelains, high soda (Na_20) and high potash (K_20). High potash feldspars are generally selected for dental porcelains because they have a high

viscosity and high resistance to pyroplastic flow. These metallic oxides are used as glass modifiers or fluxes, which lower the softening temperature of the glass by reducing the amount of cross-linking between oxygen and the glass forming elements. They are also incorporated in porcelains used for bonding to metals to increase the thermal expansion close to that of the gold alloys used in this technique.

Typical Potash Feldspar Constituents (McLean, 1979)

SiO_2	66.8%	CaO	0.45%
Na_2O	3.01%	MgO	0.13%
K_2O	10.55%	Fe_2O_3	0.30%
Al_2O_3	17.58%	TiO_2	trace

During manufacture of feldspathic dental porcelain the potash feldspar is melted at 1250^0 to 1300^0C, at which temperature the alkalis present, such as Na_20 and K_20, combine with the alumina and silica to form a potassium aluminosilicate. This glassy matrix incorporates a free crystalline silica phase, which is used to produce the "frit" by quenching the molten glass in cold water, which fragments the glass immediately. The free crystalline phase has been identified as leucite, (K_2O- Al_20_3 - $4SiO_2$), a high expansion ceramic (O'Brien, 1997). This frit is then ball milled to produce a micro-fine powder of varying particle size. The porcelain pigmentation is imparted by the addition of a concentrated colour frit, and is modified by the incorporation of a combination of various metallic oxides. Such metallic oxides impart different colours in the porcelain such as, indium-yellow, cobalt-blue, chromium-pink, iron-black, etc.

Opacifying agents such as zirconium oxide may also be incorporated in the porcelain to reduce the translucency where necessary depending on the colour or shade required. Fluorescence is found in human teeth and can be noticed when they are illuminated with lamps that emit some ultra-violet radiation, which can cause the teeth to fluoresce a bluish-white colour. This fluorescence can be produced in the dental porcelain by the incorporation of small quantities of a rare earth such as samarium (McLean, 1979).

Possible constituents of a low fusing feldspathic porcelain may be (O'Brien, 1997):

SiO_2	56.8%	AlO_2	16.3%
CaO	2.01%	K_2O	10.25%
Na_2O	8.63%	TiO_2	0.27%
ZrO_2	1.22%	Rb_2O	0.10%
UO_3	0.67%	B_2O_3, CO_2&H_2O	3.75%

1.7 Fabrication of Dental Porcelain Laminate Veneers

There are two main methods of fabricating porcelain laminate veneers

(a) Platinum foil method

(b) Refractory method

The platinum foil method involves the production of a dental stone die model from an elastomeric impression of the prepared tooth or teeth.

A matrix of platinum foil 0.02mm thick is adapted closely to the model of the prepared tooth. Folds are made in the foil matrix, which prevent the loss of shape or form of the matrix during the firing cycle, because of release of stresses in the foil during thermal expansion. The platinum foil serves a dual purpose in that it will not distort or react chemically with the porcelain during the firing cycle. The platinum foil will also provide 50μm of space, (because of the inevitable gap between the foil and the die model), between the tooth and the restoration for the bonding medium.

The refractory method also involves the production of a dental stone die model from an elastomeric impression of the prepared teeth. Once the die model has set a die relief varnish is painted over the prepared teeth to provide a 50μm thick space for the bonding medium. The prepared teeth and the teeth adjacent to them are isolated from the rest of the arch with 1.5mm modelling wax to form an enclosure into which a polyvinylsiloxane duplicating material is poured. A phosphate bonded refractory investment material is vibrated into the wax enclosure which provides an exact model of the prepared teeth which will withstand the 930^0C firing cycle without deterioration or distortion.

The low fusing feldspathic porcelain powders as supplied by the manufacturer

typically exhibit a volume porosity of 40% (McLean, 1979). During fabrication of the restorations the porcelain powders are mixed with a liquid such as distilled water to achieve a workable consistency suitable for application with a wet brush technique. The porcelains of various shades can be layered and contoured with the brush to restore the anatomical form, function and colour of the tooth being restored. Once the restoration is formed the porcelain may be condensed by hand vibration, which expels some of the air entrapped in the mass as the porcelain particles are compacted. Excess liquid may be removed from the porcelain at this stage by using paper tissues to draw the water to the surface by capillary action. The condensed porcelain water mixture is then placed in a porcelain furnace and fired or sintered at 930^0C under vacuum. The process of sintering relies on heat and the surface tension provided by the outer layer of porcelain to increase the density of the porcelain mass by eliminating the porosity between the porcelain particles. The vacuum chamber of the porcelain furnace is actually air at a reduced pressure, (101-3 k Pa), which removes air from the porcelain before sealing of the surface occurs allowing the porcelain to contract to a dense, virtually pore-free mass with a porosity of 0.08% (McLean, 1979). During the vacuum firing there is a volume contraction of the porcelain mass of about 40% which is accounted for by the removal of the 40% volume porosity present in the porcelain powder as provided by the manufacturer (O'Brien, 1997). The fired porcelain is removed from the furnace and cooled at room temperature. The surface of the porcelain is contoured and characterised with diamond burs and dental stones and the margins of the restoration are defined. The porcelain is then placed in the furnace with a non-vacuum cycle at 930^0C to glaze the surface. Glazing involves the fusion and vitrification of the outer

layer of the porcelain, which seals the micro-pores at the surface giving a non-porous, smooth, non-abrasive exterior similar in texture to that of human tooth enamel. The foil or refractory material is then removed from the porcelain and the fit surface is etched with 9% hydrofluoric acid for four minutes and then rinsed with water in an ultrasonic cleaner. Acid etching of the porcelain fit surface provides greater micro-mechanical retention for the bonding medium and can increase the tensile bond strength to the composite from 0.6MPa to 7.5MPa (Simonsen and Calamia, 1983).

1.8 AIMS OF THE STUDY

Porcelain laminate veneers are now a commonly used restorative dental treatment for masking discoloured teeth. However, there are often difficulties in matching shades clinically especially when only one tooth is treated or where the underlying teeth are badly discoloured. Thus, it is important to develop clinical protocols that allow consistent shade prescription. The purposes of this study were:

to establish if the Spectramatch GT spectrophotometer was a suitable instrument for use in the detection of colour differences among porcelain laminate veneers of different shades,

to determine the effect of various try-in media on the colour of porcelain laminate veneers and

to establish the effect of various porcelain laminate veneers on the colour of underlying tabs of various shades used to simulate the crowns of teeth.

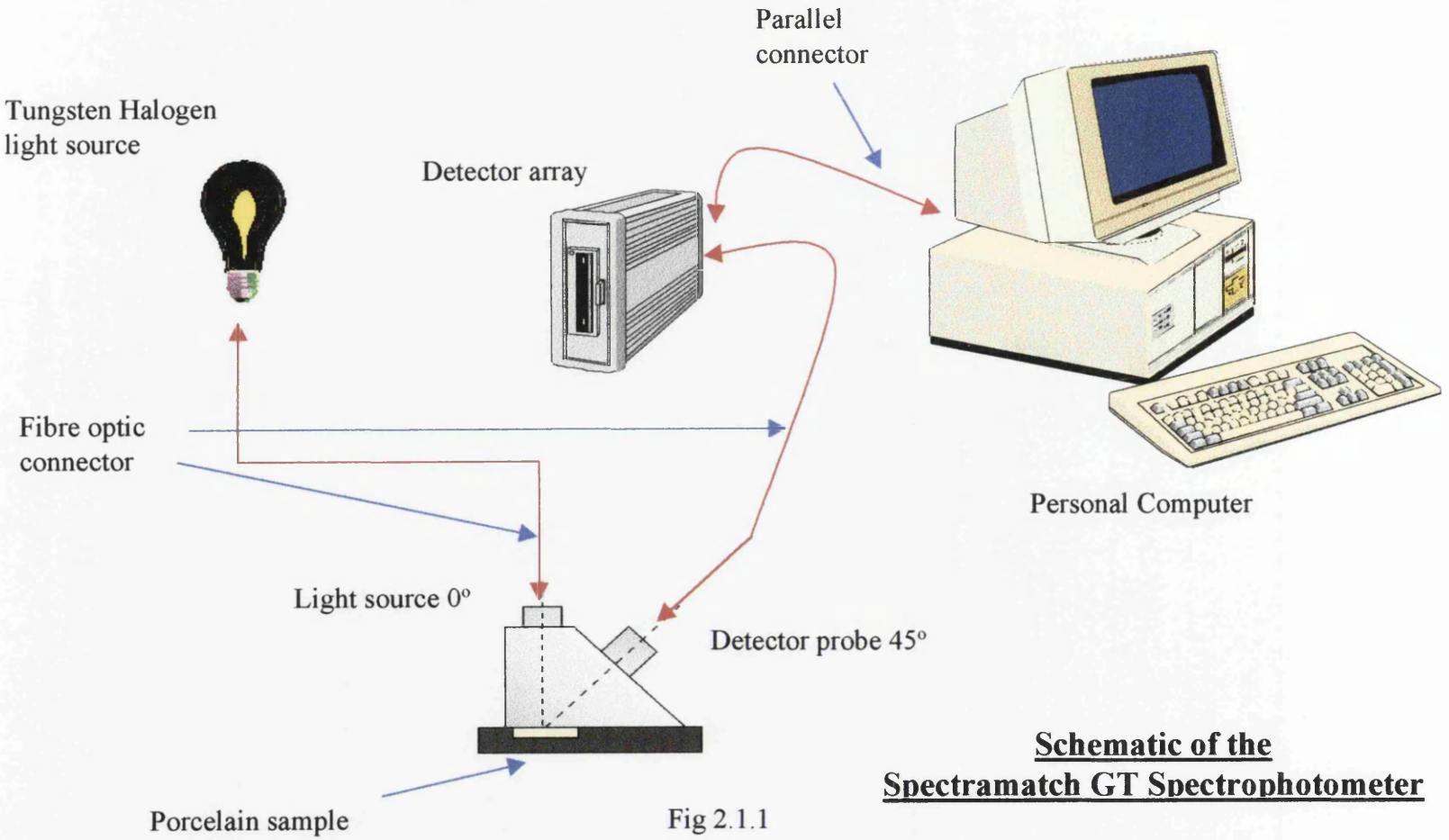
CHAPTER TWO: Materials and Methods

2.1 Spectrophotometer

In this study a Spectramatch GT Spectrophotometer, (CVI Laser Development Group, Putnam, CT, U.S.A), was used to perform instrumental colour analysis of all samples.

The Spectramatch GT is an optical fibre-based CCD Spectrophotometer connected to a Personal Computer, (133 MHz Pentium, 32 MB Ram), by means of a data acquisition card provided by the manufacturer. The light source utilised by the spectrophotometer is a high stability 20-watt tungsten-halogen lamp connected to the detector probe housing by a fibre optic cable. The detector probe can analyse a circular area, from 1.2mm to 10mm in diameter, of the illuminated specimen. The detector probe is connected to the detector array grating which analyses the spectral reflectance curves at 5 nm intervals. The instrument geometry of $0^0/45^{0,}$ (the illuminant beam is at 0^0 to the specimen and the viewing angle at 45^0), complies with the C.I.E. (International Commission On Illumination, Central Bureau of the C.I.E., Vienna, Austria) Recommended Illuminating and Viewing Conditions [Fig 2.1.1].
The Spectramatch GT Software, (CVI Laser Development Group, Putnam, CT, U.S.A), supplied with the instrument is capable of representing the 2^0 and 10^0 C.I.E. Standard Observers and also two C.I.E. Standard Illuminants i.e. Illuminant A and Illuminant D65.

Prior to using the spectrophotometer, the instrument and controlling software must



Schematic of the Spectramatch GT Spectrophotometer

Fig 2.1.1

be calibrated and optimised to ensure accurate performance. Calibration and optimisation were carried out as described below.

2.1.1 Calibration

The manufacturer provides a default calibration set that contains the data, which relates a pixel value to a known wavelength. This calibration set was suitable for measuring the Percentage Reflection Data of all the samples in this study, and was used throughout.

2.1.2 System Response

Before using the spectrophotometer for any measurements the system response must be optimised for percentage reflection by setting the three system variables of, Integration Time, Signal Averages & Light Source.

2.1.3 Integration Time

The Integration Time is the amount of time in which the detector elements store the charge from the input signal, and is specified in milliseconds.

This is configured by placing the detector probe on the Spectrolon White Reference Standard, (CVI Laser Development Group, Putnam, CT, USA), supplied by the manufacturer and selecting Scope Mode. While using the Scope Mode, data is displayed continuously on the screen in the form of the System Response Graph. The

System Response Graph shows signal intensity (y-axis) vs. detector pixels (x-axis). Pixels range from 1 to 2048, with pixel 1 corresponding to the shortest wavelength and pixel 2048 to the longest. Intensity ranges from 0 to 4096 with 0 being the lowest intensity that can be measured and 4096 the greatest. The Integration Time is adjusted to give a maximum peak in the response curve of the displayed graph reaching an intensity of between 3800 and 4000. In the case of this instrument the Integration Time was set at 65 milliseconds for all measurements in this study.

2.1.4 Signal Averages

The Signal Average configuration allows the user to select how many scans of data will be used in sample scans. The software can be configured to select how many times the sample is scanned, average the data collected and present the output, thus improving the precision of the measurements. The default set by the manufacturer of 9 signal averages per scan was found to be too slow, and consequently signal averages for all measurements in this study were set at 4 per scan.

2.1.5 Light Source

The Light Source used with this instrument was the AS-220-F, a high stability 20-watt tungsten-halogen lamp, (CVI Laser Development Group, Putnam, CT, U.S.A), supplied by the manufacturer. This lamp has a fixed output, and as such requires no optimisation, other than allowing the bulb to warm up for 5 minutes to stabilise output prior to any use of the instrument.

2.1.6 C.I.E. Standard Observer

The C.I.E. recommended standard observer of 2^0 gives a field of view of 1.7cm from a viewing a distance of 50cm. . A standard observer of 2^0 was used throughout this study as this more closely represents the viewing angle, distance and field of view during tooth shade selection, than the 10^0 standard observer.

2.1.7 C.I.E. Standard Illuminant

C.I.E. Standard Illuminant D_{65}, which represents average daylight including the ultraviolet wavelength region, was used as the illuminant for all colour analysis throughout this study. The Spectramatch GT software uses the known light output from the light source, and determines the data for measurements under the selected illuminant through calculations based on the data actually measured under the instruments light source, and the illuminant's spectral distribution data stored in the software memory.

2.1.8 Percentage Reflectance Graph

The Spectramatch GT spectrophotometer is capable of obtaining transmission, reflectance or absorbance data from the samples analysed. In this study all specimens were analysed for reflectance data. The Percent Reflectance Graph is used to compute the percentage reflection of the test sample with respect to some other sample. A Percent Reflectance Graph is calculated using three scans.

2.1.9 Background Scan.

This scan determines the background level in the system. The background scan is set by directing the detector probe towards a dark area under a worktop or blocking the aperture, thereby ensuring that no light is reflected into or enters the detector probe.

2.1.10 Full Scan

The light source is turned on for 5 minutes prior to the full scan, and the White Reflectance Standard, to which the sample is compared, is loaded on the detector probe. The C.I.E. data recorded for the Spectrolon White Reference Standard was as follows:

L* 99.92 a* 0.10 b* 0.24

The full scan provides the reflection data to which the reflection of the test sample will be compared. The test sample is said to be "normalised" to the full scan sample.

2.1.11 Sample Scan

The light source should be on for 5 minutes prior to the sample scan and the test sample loaded to the detector probe.

Each point on the percent graph is calculated using the following formula:

$$percentage = \frac{(sample) - (background)}{(full) - (background)}(100)$$

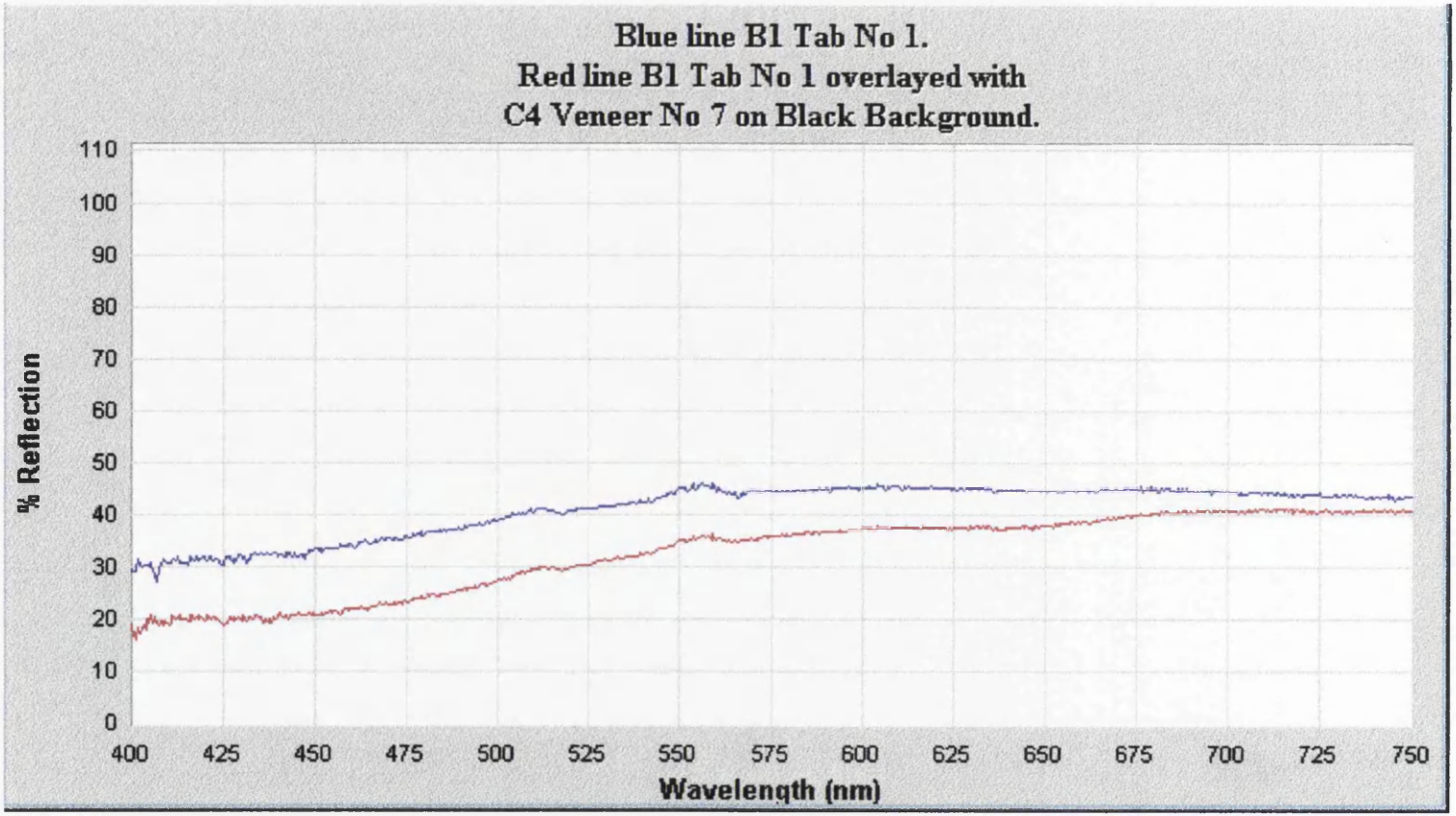
The pixel values in the percent graph will be converted to their corresponding wavelength. During the preparation of the normalisation sample the percent value of the normalisation sample is set. In this study the default of 100% was used for all sample measurements. Prior to acquiring percent reflectance data, the normalisation options were set to " Normalise to Reference". The "Background Subtract" option was also selected for all measurements, which is used to acquire system background noise in determining the 0-100% range on the y-axis.

2.1.12 Spectral Reflectance Graph

The data acquired from the spectral reflectance analysis is plotted as the spectral reflectance curve of the sample in a graph plotting percentage reflectance from 0% to 110% on the y axis against wavelength from 400nm to 750nm (the visible spectrum) on the x axis [Fig 2.1.2].

2.1.13 Tristimulus Values

The Spectramatch GT software calculates the C.I.E. Tristimulus Values X, Y & Z, (where X corresponds to red, Y to green and Z to blue). This is done by multiplying the spectral power distribution of the Standard Illuminant, (in this case C.I.E. Illuminant D_{65}), the colour matching functions for Illuminant D_{65} and the spectral reflectance data of the specimen. The data from the tristimulus values can then be used to calculate other values in colour space, such as C.I.E. L*a*b* colour space values.



The Spectramatch GT spectrophotometer analyses the spectral reflectance curve of the porcelain specimens and generates a line graph in the visible range of the spectrum (400 - 750 nanometers).

Fig 2.1.2 **Spectral Reflectance Graph**

2.1.14 L*a*b* Colour Space Values

The Spectramatch GT software calculates the L*a*b* colour space values (where L* corresponds to lightness, a* to red in the positive and green in the negative & b* to yellow in the positive and blue in the negative) from the tristimulus data.

2.1.15 ΔE Colour Difference

The ΔE Colour Difference between a standard white and a sample or any two samples is calculated by the Spectramatch GT software from the L*a*b* colour space values using the following formula:

$$\Delta E^{*}ab = \sqrt{(\Delta L^{*})^{2} + (\Delta a^{*})^{2} + (\Delta b^{*})^{2}}$$

In this formula ΔL* is the difference in lightness between the two samples, Δa* the difference in the red-green value and Δb* the yellow-blue.

The ΔE Colour Difference values were used to compare and contrast all specimens throughout this study [Fig 2.1.3].

Computer software uses the data from the spectral analysis to generate the C.I.E. colour information.

Fig 3 is representative of the data collected and displays the colour data for a B1 2.5mm tab on the left and the B1 tab overlaid with a C4 0.5mm veneer.

Value L* is the lightness factor, a* is red in the + and green in the -, and b* is yellow in the + and blue in the -.

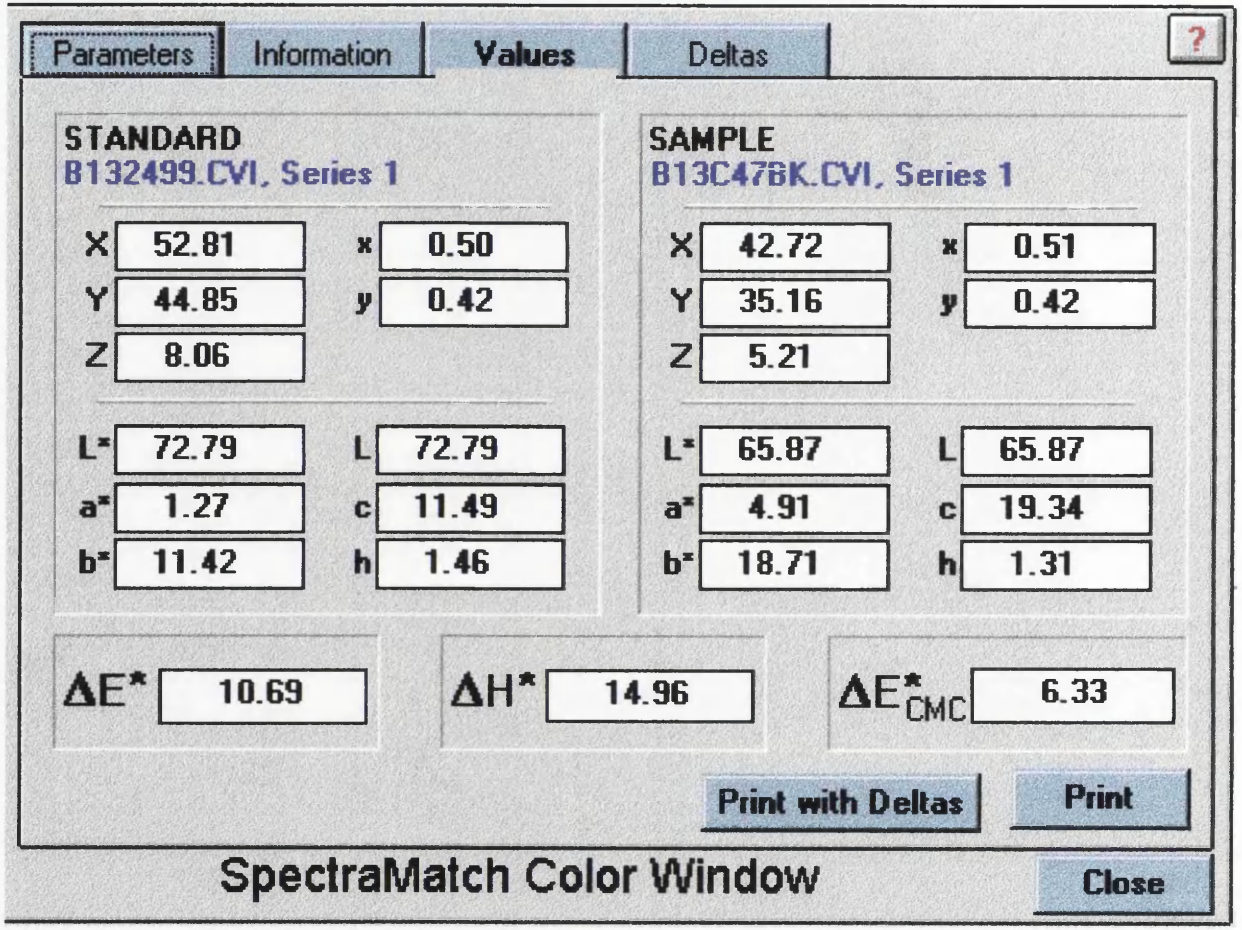


Fig 2.1.3 **SpectraMatch Colour Window**

2.2 Pilot Study No 1

2.2.1 Pilot Study No 1 Materials & Methods

A pilot study was conducted to assess the ability of the Spectramatch GT Spectrophotometer to discern the colour difference between a custom made 12mm diameter x 0.5mm thick matte black polycarbonate plastic disc and a custom made 12mm diameter x 0.5mm thick matte white polycarbonate plastic disc. The discs were hand polished on a glass platten with 1200 grit White Bauxilite Honing Abrasive 2000, (Raymond A Lamb, London, U.K.), to ensure a uniform gloss and surface texture. The discs were marked on the lower edge of the upper surface with a scalpel to ensure accurate, repeatable orientation to the detector probe. A custom enclosure was fabricated with opaque matte black polycarbonate plastic, around the detector probe of the Spectramatch GT Spectrophotometer, to prevent any extraneous light entering the probe. The enclosure enabled accurate and repeatable presentation of the sample surface to the detector probe at 90^0. The enclosure incorporated a 12mm x 0.5mm-diameter recess to allow the sample discs to be presented flush to the surface of the detector probe, to maintain the $0^0/45^0$ geometric relationship of the detector. Each disc was measured ten times removing and replacing the detector probe between each measurement. The samples were compared separately to the white reference standard provided by the manufacturer. The C.I.E. Tristimulus values were calculated and the spectral reflectance curves plotted and recorded in graph form by the Spectramatch GT software supplied with

the instrument. This software was also used to analyse this data and convert this information to C.I.E. L*a*b* notation and C.I.E. Colour Differences (ΔE).

2.2.2 Pilot Study No 1 Results

The results of the pilot study are shown in [Table 2.2.2]. There was a mean ΔE L*a*b* Colour Difference of 82.46 units between the black and white samples.

2.2.3 Pilot Study No 1 Discussion

This pilot study demonstrated that the Spectramatch GT Spectrophotometer was capable of discerning an acceptable range of C.I.E. ΔE L*a*b* Colour Differences between the black and white disc. The pilot study also proved that the instrument was capable of reproducing consistent and repeatable measurements of the colour of the white disc with a low standard deviation between the ten measurements. The ten measurements of the black disc had a higher standard deviation than that of the white, and there was a progressive increase in the colour difference from pass 1 to 10. The probable cause of this was due to a cumulative heating effect of the surface of the sample from the light source. The higher absorbance of transmitted light in the black compared with that of white sample could account for the larger differences in the measurements of the two samples (Berger-Schunn, 1994). For this reason it has been recommended that the background of the sample holders for colour measurements is white (Berger-Schunn, 1994). The measurement error for non-

Colour Difference of Discs Compared to White Standard		
	Black Disc	White Disc
Pass 1 ΔE	80.53	2.59
Pass 2 ΔE	80.84	2.61
Pass 3 ΔE	85.74	2.65
Pass 4 ΔE	86.1	2.71
Pass 5 ΔE	86.55	2.71
Pass 6 ΔE	86.89	2.7
Pass 7 ΔE	87.12	2.71
Pass 8 ΔE	87.35	2.69
Pass 9 ΔE	87.61	2.68
Pass 10 ΔE	87.62	2.69
Mean	85.1400	2.6713
STDEV	2.79997	0.04853

Table 2.2.2

opaque or translucent samples, such as the porcelain samples used in this study, will be smaller than if a black background was used (Berger-Schunn, 1994)

2.3 Pilot Study No2

2.3.1 Pilot Study No 2 Materials & Methods

A second pilot study was conducted to assess the ability of the Spectramatch GT Spectrophotometer to discern the small colour differences between the 16 different porcelain shade tabs of the Vita Lumin Vacuum Shade Guide, (Vita Zahnfabrik, Bad Sackingen, Germany).

The porcelain tabs were taken from the Vita Lumin Vacuum Shade Guide holder. A custom holder was fabricated with Lab Putty, (Coltene/Whaledent Inc., Mahwah, NJ, USA), which allowed accurate and repeatable alignment of the central one third of the shade tabs at 90^0 to the detector probe of the spectrophotometer. The central one third of the shade guide tab was taken as representative of the body, (or dentine), shade of porcelain indicated in the porcelain build up recommended by the manufacturer, (Vita Zahnfabrik, Bad Sackingen, Germany), required to replicate each shade in the guide. Each of the dentine shades in this instance requires a different shade of porcelain powder and therefore the colours should be distinctly different from each other. A matte black opaque plastic enclosure was fabricated around the custom holder to eliminate any extraneous light entering the detector probe. The detector probe of the spectrophotometer was aligned at right angles to the surface of each of the 16 samples in turn and colour analysis performed. This measurement was repeated six times for each of the 16 shades in the shade guide. The C.I.E. Tristimulus values were calculated and the spectral reflectance curves

plotted and recorded in graph form by the Spectramatch GT software supplied with the instrument. This software was also used to analyse this data and convert this information to C.I.E. L*a*b* notation and C.I.E. Colour Differences (ΔE) as described previously.

2.3.2 Pilot Study No 2 Results

The results were recorded and are shown in [Table 2.3.2.1], which illustrates the measured lightness of the samples, with the lightest shade on the left progressing to darkest on the right, and [Table 2.3.2.2], which illustrates the ΔE Colour Differences compared to the white reference standard.

2.3.3 Pilot Study No2 Discussion

The Vita Lumin Shade Guide samples were compared to the Spectrolon white reference standard and therefore the lightness of the sample increased as the colour difference decreased i.e. the smaller the colour difference between the sample and the white reference standard is, the lighter the sample is.

The high standard deviations of many of the shade groups measured, and the lack of any good correlation with the lightness order published by the manufacturer, (Vita Zahnfabrik, Bad Sackingen, Germany), with the measured lightness values of the samples was unsatisfactory. This apparent lack of correlation with the Vita published order and independent measurements is consistent with findings by other

Vita Lumin Published Order of Lightness															
B1	A1	B2	D2	A2	C1	C2	D4	A3	D3	B3	A35	B4	C3	A4	C4
Measured Order of Lightness of Vita Shade Tabs Compared to White Standard															
A1	A2	B1	C1	B2	A3	D2	D3	C2	B3	C3	B4	D4	A35	A4	C4

Table 2.3.2.1

Colour Difference of Vita Lumin Shade Guide Tabs Compared to the White Standard																
	A1	A2	A3	A35	A4	B1	B2	B3	B4	C1	C2	C3	C4	D2	D3	D4
PASS 1	26.63	29.62	30.94	36.12	38.09	28.83	32.14	32.64	33.62	33.0	32.48	35.05	40.2	34.35	32.55	33.89
PASS 2	28.0	27.28	35.17	39.13	38.85	35.43	33.29	38.91	40.49	30.0	35.68	36.85	41.75	30.5	35.28	41.0
PASS 3	27.79	27.65	34.91	40.0	36.68	35.16	33.21	38.84	40.08	30.0	35.29	36.33	42.0	30.5	33.49	41.21
PASS 4	26.46	29.24	31.59	35.42	38.0	29.07	32.12	33.3	33.33	32.86	33.33	34.72	40.22	33.85	32.55	34.19
PASS 5	26.66	29.82	31.47	35.82	38.07	29.0	32.14	33.49	33.33	32.89	33.43	33.49	40.22	33.7	32.42	34.35
PASS 6	26.48	29.24	31.11	35.75	37.85	29.09	32.14	33.2	33.23	32.84	33.43	34.92	40.32	33.59	32.43	34.42
MEAN	27.0	28.81	32.53	37.0	37.93	31.1	32.51	35.06	35.68	31.93	33.94	35.23	40.78	32.75	33.12	36.51
STDEV	0.693	1.071	1.959	1.988	0.703	3.252	0.576	2.966	3.572	1.502	1.255	1.204	0.843	1.761	1.133	3.565

Table 2.3.2.2

researchers (Miller, 1994).

The possible reasons for the inaccuracies were:

(a) The detector probe could not be presented flush with the surface of the shade guide tab, as the shade guide tab has a convex uneven surface.

(b) There was no way of knowing what was actually being measured because of the gradations of several layers of dental porcelain of different colours in each of the tabs.

(c) The surface texture of the tabs had a high gloss finish with an undulating contour.

(d) The tabs had a translucent upper surface of unknown dimension with an opaque sub-stratum at an unknown depth.

It had been hoped to use the Vita Lumin Shade Guide tabs as the base shades on which the porcelain veneers would be measured against in the main part of this study, but because of the disappointing results of the pilot study this was abandoned.

2.4 Main Study

2.4.1 Comparison of Two Adjacent Shades

This experiment was carried out to assess the capability of the Spectramatch GT Spectrophotometer to discern small colour differences between two adjacent shades of Shofu Vintage Dental Porcelain Veneers, (Shofu Inc. Kyoto, Japan), of Body Shades A3 & A4. The porcelain veneers were fabricated to be 0.5mm thick, which would be the optimum thickness clinically, replacing the 0.5mm enamel reduction without altering the labial profile of the tooth. The porcelain veneers were made as 12mm diameter circular discs, which would ensure that the maximum 10mm measuring circle of the detector probe aperture was measuring only the colour of the porcelain.

An acetyl resin rod, 12mm in diameter, was cut with a Labcut 1010 Diamond Disc, (Agar Scientific Ltd, Cambridge, UK), to form 16, 12mm x 0.5mm discs, to make templates for the fabrication of the dental porcelain custom veneers. The resin discs were sealed with modelling wax to the base of a custom plastic former and impressions taken with Pourable Silicone duplicating material (Chaperlin & Jacobs, Sutton, Surrey U.K.) A white-paraffin separating barrier was applied to the impressions to facilitate separation of a further layer of Pourable Silicone duplicating material poured into the impressions to form a mould. Lamina Vest Refractory Investment, (Shofu Inc. Kyoto, Japan), was mixed at the ratio of 40g powder to 6ml liquid according to manufacturer's instructions, and vibrated into the moulds and left

to set for 1 hour. The refractory dies were removed from the moulds and placed in a Kavo EWL Preheating Furnace, (Kavo, Elektrotechnisches Werk, Germany) at room temperature. The temperature was raised to 700°C over a period of 1 hour, and held for 15 minutes to dry the investment moulds and remove any chemical impurities. The refractory moulds were then placed in a Vita Vacumat 100 Porcelain Furnace, (Vita Zahnfabrik, Bad Sackingen, Germany), and raised from 600°C to 980°C over 3 minutes in air, and held for 5 minutes to harden the refractory as indicated in the manufacturer's instructions. Shofu Vintage Dentine Porcelains, (Shofu Inc. Kyoto, Japan), of shades A3 & A4 were mixed with distilled water and applied to the refractory moulds with a brush and condensed by hand in the normal manner employed by dental technicians. The same operator fabricated all samples. The samples were inserted into the porcelain furnace at 600°C, dried at the entrance chamber for 4 minutes, and the temperature increased to 920°C, over a period of 6 minutes under vacuum, and the temperature held at 920°C for 30 seconds, according to manufacturers instructions. The 0.5mm veneers required one further correction vacuum firing at 910°C to compensate for contraction during firing. The veneers were then glazed in the porcelain furnace in air at 920°C for 1.5 minutes.

The veneers were hand finished on the upper surface, using Meisinger K & B Green Silicone Carbide Abrasive Points, (Chaperlin & Jacobs, Sutton, UK), in a laboratory handpiece to the refractory mould level. The refractory moulds were removed with 20 p.s.i. air pressure and 50μm Ceramic Blasting Beads, (Renfert, Hilzingen, Germany), in a Keramo 3 Microblasting Unit, (Renfert, Hilzingen, Germany), which left the porcelain surface intact.

The lower surfaces of the veneers were sealed with sticky wax to the sample holder of the Kent 3, Automatic Lapping & Polishing Unit, (Kemet International Ltd, Maidstone, UK). The sample holder was attached to the lapping unit, perpendicular to the abrasion platten, and the upper surfaces abraded with Bra-Met 240 grit Abrasive Discs, (Kemet International Ltd, Maidstone, UK), for a period of 15 minutes to ensure a uniformly flat surface. The samples were removed and this process was repeated on the lower surface of the specimens to ensure planar parallelism of the upper and lower surfaces. This would ensure each that each sample was presented to the spectrophotometer perpendicular to the detector probe. The central points of each sample were measured with a Digital Micrometer (Mitutoyo, Tokyo, Japan) to assess the amount of hand finishing required. The veneers were hand finished on a glass platen with 1200 grit White Bauxilite Honing Abrasive 2000, (Raymond A Lamb, London, UK), to 0.5mm (± 40 μm). This procedure also ensured that the surface textures of the samples were uniform, and that there would be complete and even contact between the veneer and the sample holder background.

The following samples were produced:

Shofu Vintage Dentine Shade A3	Shofu Vintage Dentine Shade A4
8 x (0.5mm x 12mm) Veneers	8 x (0.5mm x 12mm) Veneers
(Batch No 019603)	(Batch No 049556)

A custom enclosure was fabricated with opaque matte black plastic, around the

detector probe of the Spectramatch GT Spectrophotometer, to prevent any extraneous light entering the probe. The enclosure enabled accurate and repeatable presentation of the sample surface to the detector probe at 90^0.

Spectral analysis of all specimens was performed using C.I.E. standard configurations of 2^O observer, $0/45^O$ measuring geometry and Illuminant D65 conditions. The colour of each specimen was measured against black and white backgrounds, and recorded in C.I.E. L*a*b* notation, (International Commission on Illumination, Central Bureau of the C.I.E., Vienna, Austria). The colour difference (ΔE) between each veneer specimen and the Spectrolon white reference standard provided by the manufacturer was calculated as described previously.

2.4.2 Comparison of Base Shade Tabs of the Same Shade

It was decided to fabricate custom base shade tabs, because of the problems encountered with measurement of the Vita Lumin Shade Guide Tabs, in an effort to ensure homogeneity of material content and colour in the samples. Base shade tabs, which were to represent the tooth to be veneered, were manufactured from the body, (or dentine), porcelain powders of the relevant shade, to simulate the middle third colour of the tooth, as per the manufacturer's prescription. Because of the possibility of manipulative variables affecting the colour of the base shade tabs it was decided to assess the operator's ability to produce base shade tabs of the same colour during custom fabrication. To this end the same operator fabricated eight base shade tabs of shade A3 body porcelain. These base shade tabs were 2.5mm thick, and this should negate any significant effect of the background colour of the custom sample

holder (Swift, Hammel and Lund, 1994). The base shade tabs were made as 12mm diameter circular discs which would ensure that the maximum 10mm measuring circle of the detector probe aperture was measuring only the colour of the porcelain. The methods described previously in the fabrication of the 0.5mm porcelain veneer samples were employed in the production of the base shade tabs. Because of the greater volume of porcelain used to produce the tabs, a third correction vacuum firing at 910°C was necessary to compensate for contraction during firing. The samples were then glazed and the surfaces finished as described for the veneer samples.

The following samples were produced:

Shofu Vintage Dentine Shade A3

8 x (2.5mm x 12mm) Base Shade Tabs

(Batch No 019603)

Colour analysis of each the base shade tabs was performed on black and white sample holder backgrounds as described for the veneer samples, and compared to the Spectrolon White Reference Standard. The colour differences between each base shade tab and the white reference standard were calculated and recorded.

2.4.3 Fabrication of the Base Shade Tab and Veneer Combinations

Custom base shade tabs and veneers were fabricated, using the same methods as described previously, to assess the effect of different veneer-tab combinations on

colour. The samples produced were as follows:

Shofu Vintage Dentine	Shofu Vintage Dentine
Base Shade Tabs (2.5mm x 12mm)	Veneers (0.5mm x 12mm)
5 x Shade A3 (Batch No 019603)	8 x Shade A3 (Batch No 019603)
5 x Shade B1 (Batch No 029527)	8 x Shade B1 (Batch No 029527)
5 x Shade B4 (Batch No 079539)	8 x Shade B4 (Batch No 079539)
5 x Shade C4 (Batch No 059529)	8 x Shade C4 (Batch No 059529)

Three shades were selected as a cross section of light to dark shades according to the Vita Lumin Vacuum Shade Guide Lightness Order i.e. B1 the lightest shade, A3 a mid range shade and C4 the darkest shade. B4 was chosen as another dark shade representative of tooth discolouration, where clinically, porcelain laminate veneers may be recommended as a treatment option.

2.4.4 Selection of Representative Shade Tabs

Colour analysis of the five base shade tabs of each of the four shades, (A3, B1, B4 & C4), was performed, and the colour difference (ΔE) between each tab and the Spectrolon white reference standard calculated as described previously. The mean of the colour differences for each shade was calculated and the sample closest to the mean was taken to be representative of that shade.

2.4.5 Colour Reproduction of Veneer Samples

Colour analysis of the eight veneers of each of the four shades, (A3, B1, B4 & C4), was performed, and the colour difference (ΔE) between each veneer and the Spectrolon white reference standard calculated as described previously. This analysis was carried out to assess the uniformity of colour reproduction between each of the eight veneers of the same shade.

2.4.6 Assessment of Reproducibility of Colour Measurement

Colour analysis of each of the eight veneers of the four different shades, (A3, B1, B4 & C4) placed over the A3 representative base shade tab was performed twice separated by three hours. This was done to assess the reproducibility of Spectramatch GT Spectrophotometer colour measurements, and also to ensure that there was repeatable and accurate operator placement and alignment of the samples.

2.4.7 Colour Measurement of Base Tabs & Veneers with Air

Colour analysis of each of the eight veneers of the four different shades, (A3, B1, B4 & C4), placed over the four representative base shade tabs was performed and the data recorded. All measurements were performed with air as the medium between the base shade tabs and veneers. The colour of the base shade tabs and veneer combinations were compared to the colour of the representative base shade tab of

the same shade and the colour difference (ΔE) calculated. The mean colour difference (ΔE) for each of the eight base shade tab and veneer combinations was calculated.

2.4.8 Colour Measurement of Base Tabs & Veneers with Try-In Media

A series of colour measurements of each of the eight veneers of the four different shades, (A3, B1, B4 & C4), placed over the four representative base shade tabs, was performed with three different try-in mediums placed between the tabs and veneers to assess their effect on colour.

The try-in media were:

1. Distilled Water
2. Glycerine (Supercook, Leeds, UK)
3. Duo-Cure Bonding Cement Base/Try-In Paste (Terec Ltd, Sunbury on Thames, UK), (Batch No GJ57)

The three try-in media were placed as a thin film between each veneer and tab during colour measurements. The veneer was placed with light finger pressure over the base shade tab. Because of the planar parallelism of the veneer and tab surfaces, the thickness of the distilled water and glycerine mediums ranged from 4 to 9μm, and the thickness of the base/try-in paste medium ranged from 10 to 14μm. Colour analysis of each of the eight veneers of the four different shades, (A3, B1, B4 & C4), placed over the four representative base shade tabs with distilled water as the try-in

medium was performed and the data recorded. The colour of the base shade tabs and veneer combinations were compared to the colour of the representative base shade tab of the same shade and the colour difference (ΔE) calculated. The mean colour difference (ΔE) for each of the eight base shade tab and veneer combinations was calculated.

The same measurements and calculations were also carried out for the glycerine and base/try-in paste media.

2.4.9 Colour Difference of Veneer Shades A3, B1, B4 & C4 over Base Shade Tabs of A3, B1, B4 & C4, compared to the Representative Tab of the Same Shade.

The colour difference of each of the veneer shades over all four base shade tabs with distilled water as the medium compared to the representative tab of the same shade was calculated. Distilled water was used as the try-in medium as it had given the most consistent results with the least variability in colour in the previous experiments.

This comparison was carried out to assess the influence the veneer had on the overall colour of the combined veneer and base shade tab. Each of the eight veneers of each of the four shades was placed over the representative base shade tab and the colour difference between the combination and the representative base shade tab calculated. This was done for each of the four shades and the mean colour difference for each veneer tab combination calculated.

2.4.10 Assessment of the Clinical Significance of the Colour Difference between Veneer / Tab Combinations and the Base Shade Tabs.

Research by Johnston and Kao, (1989) has shown that a C.I.E. L*a*b* ΔE Colour Difference of 3.7 is the average acceptable limit for shade matches in the oral environment when comparing composite resin veneers to their adjacent teeth. This figure was used in this study to assess whether the four 0.5mm veneer shades investigated were capable of producing an acceptable shade match to the representative base shade tab of the same shade, when placed over the various base shade tabs. As an example, if a Shade C4 veneer of 0.5mm is placed over the B4 base shade tab and the resultant colour compared to the colour of the C4 representative base shade tab, was the C.I.E. ΔE Colour Difference less than or equal to 3.7? If the colour difference was higher than 3.7 the veneer tab combination was not an acceptable match and the veneer deemed to be incapable of reproducing the desired shade at 0.5mm thickness with the underlying base tab. If the colour difference was 3.7 or lower the combination of veneer and tab was acceptable as a shade match for the for the representative shade tab and capable of combining with the underlying colour to reproduce the desired shade.

2.4.11 Statistical Analysis

The results were analysed statistically with Minitab Version 9.2 (Minitab Inc., State College, PA, USA), and parametric tests including ANOVA and Student t Test, at 95% Confidence Interval, to compare pairs of means were used. Analysis showed the samples to be normally distributed.

CHAPTER THREE: Results

3.1 Results

Comparison of Two Adjacent Shades

The results of the colour analysis of the porcelain veneers of each of the two shades measured against black and white backgrounds are shown in Table 3.1.1 & Table 3.1.2 respectively. The mean colour difference, (ΔE), between the shade A3 and shade A4 veneers measured on the black background was 2.67. The mean colour difference between the shade A3 and shade A4 veneers measured on the white background was 8.19.

Comparison of Base Shade Tabs of the Same Shade

The results of the colour measurement of the eight base shade tabs of shade A3 measured on white and black backgrounds compared to the white reference standard are shown in Table 3.1.3. The standard deviation of the A3 samples measured on white background was 0.7502, and 0.9942 for the samples measured on the black background.

Selection of Representative Shade Tabs

One tab from each of the four shades was chosen as representative of the shade group by selecting the tab closest to the mean colour difference of the five tabs. The results of this selection process can be seen in Table 3.1.4, as illustrated by the

Veneers on Black Background Compared to White Reference Standard				
	Thickness (mm)	A3 ΔE	Thickness (mm)	A4 ΔE
Sample 1	0.498	36.77	0.47	38.03
Sample 2	0.464	36.6	0.486	41.78
Sample 3	0.49	36.9	0.51	38.72
Sample 4	0.497	35.92	0.516	39.63
Sample 5	0.492	37.26	0.515	37.98
Sample 6	0.5	38.19	0.494	39.07
Sample 7	0.5	36.02	0.519	39.97
Sample 8	0.497	36.06	0.495	39.93
Mean	0.492	36.72	0.501	39.39
STDEV	0.0120	0.7623	0.0173	1.2414

Table 3.1.1

Veneers on White Background Compared to White Reference Standard				
	Thickness (mm)	A3 ΔE	Thickness (mm)	A4 ΔE
Sample 1	0.498	21.3	0.47	28.22
Sample 2	0.464	20.24	0.486	27.75
Sample 3	0.49	19.63	0.51	28.52
Sample 4	0.497	20.11	0.516	28.49
Sample 5	0.492	19.74	0.515	28.29
Sample 6	0.5	20.73	0.494	28.53
Sample 7	0.5	19.74	0.519	29.34
Sample 8	0.497	20.67	0.495	28.56
Mean	0.492	20.27	0.501	28.46
STDEV	0.0120	0.5892	0.0173	0.4447

Table 3.1.2

A3 Base Shade Tabs Compared to White Reference Standard			
	Thickness (mm)	**White Background**	**Black Background**
Sample 1	2.484	34.62	34.32
Sample 2	2.478	32.2	33.34
Sample 3	2.486	33.61	35.57
Sample 4	2.497	33.69	34.85
Sample 5	2.485	33.13	34.52
Sample 6	2.496	33.18	32.61
Sample 7	2.465	32.51	34.02
Sample 8	2.495	33.57	35.35
Mean	2.486	33.31	34.32
STDEV	0.0108	0.7502	0.9942

Table 3.1.3

Base Shade Tabs Compared to White Reference Standard								
		ΔE		ΔE		ΔE		ΔE
	Thickness (mm)	A3 (2.5)	Thickness (mm)	B1 (2.5)	Thickness (mm)	B4 (2.5)	Thickness (mm)	C4 (2.5)
Sample 1 ΔE	2.484	34.00	2.500	26.92	2.497	37.17	2.497	41.67
Sample 2 ΔE	2.478	31.65	2.500	22.98	2.495	36.92	2.500	41.63
Sample 3 ΔE	2.465	31.96	2.496	23.90	2.499	37.83	2.499	41.95
Sample 4 ΔE	2.495	32.97	2.503	25.77	2.498	37.75	2.499	40.58
Sample 5 ΔE	2.496	28.54	2.504	25.54	2.496	37.95	2.501	39.33
Mean	2.484	31.824	2.501	25.022	2.497	37.524	2.499	41.032
STDEV	0.013	2.054	0.003	1.570	0.002	0.452	0.001	1.085

Shaded cells indicate sample closest to the mean for each shade

Table 3.1.4

shaded cells.

Colour Reproduction of Veneer Samples

The eight veneers of each shade group were assessed for uniformity of colour reproduction of the specified shade. The results are shown in Table 3.1.5.

Assessment of Reproducibility Colour Measurement

The eight veneers of each shade group were placed over the representative A3 base shade tab number 3, with an air medium between them, and colour analysis performed at baseline and three hours later. The results are shown in Table 3.1.6. Statistical analysis showed no significant difference between the two sets of measurements, with p values of;

A3 Veneers p=0.32

B1 Veneers p=0.71

B4 Veneers p=0.95

C4 Veneers p=0.79

Colour Measurement of Base Tabs & Veneers with Air

Each of the eight veneers of the four shade groups was placed over the representative shade tab of each of the four shades, with an air medium between them. The mean colour differences between the tab and veneer combinations and the base shade tab of the same shade as the veneer group were calculated.

The results are shown in Tables 3.1.7, 3.1.8, 3.1.9 & 3.1.10.

Veneers Compared to White Reference Standard								
	Thickness (mm)	ΔE	Thickness (mm)	ΔE	Thickness (mm)	ΔE	Thickness (mm)	ΔE
Shade		A3 (0.5)		B1 (0.5)		B4 (0.5)		C4 (0.5)
Sample 1 ΔE	0.498	20.79	0.497	12.98	0.496	24.44	0.498	28.64
Sample 2 ΔE	0.464	19.68	0.499	13.72	0.489	25.82	0.493	27.77
Sample 3 ΔE	0.49	19.12	0.5	13.01	0.498	25.76	0.499	28.87
Sample 4 ΔE	0.497	19.61	0.497	13.15	0.492	26.3	0.498	28.54
Sample 5 ΔE	0.492	19.25	0.499	12.83	0.494	24.99	0.494	28.7
Sample 6 ΔE	0.5	20.24	0.499	14.19	0.497	26.08	0.497	28.64
Sample 7 ΔE	0.5	19.22	0.499	13.81	0.499	24.71	0.495	28.74
Sample 8 ΔE	0.497	20.16	0.495	13.55	0.493	26.01	0.495	28.37
Mean	0.492	19.76	0.498	13.41	0.495	25.51	0.496	28.53
STDEV	0.01196	0.59058	0.00164	0.48297	0.00337	0.69824	0.00217	0.34142

Table 3.1.5

A3 Tab No3 and veneers with Air at Baseline						A3 Tab No3 and veneers with Air 3 hours Later					
Colour Difference compared to Tab A3						Colour Difference compared to Tab A3					
	A3 Tab	Veneer	Veneer	Veneer	Veneer		A3 Tab	Veneer	Veneer	Veneer	Veneer
Shade		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**	**Shade**		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**
Sample 1 ΔE		3.28	8.91	1.63	4.48	**Sample** 1 ΔE		3.49	8.88	1.62	4.73
Sample 2 ΔE		3.74	8.78	2.23	4.52	**Sample** 2 ΔE		3.95	8.59	2.1	4.43
Sample 3 ΔE	**31.96**	4.19	9.26	2.1	5.04	**Sample 3** ΔE	**31.96**	4.42	9.27	1.93	4.73
Sample 4 ΔE		3.66	9.12	2.23	4.55	**Sample** 4 ΔE		3.82	8.83	2.15	4.45
Sample 5 ΔE		3.69	8.78	1.67	4.33	**Sample** 5 ΔE		3.85	8.85	2.15	4.42
Sample 6 ΔE		3.49	7.88	2.09	4.53	**Sample** 6 ΔE		3.56	7.89	2	4.72
Sample 7 ΔE		4.63	8.61	1.72	4.67	**Sample** 7 ΔE		4.74	8.6	1.67	4.76
Sample 8 ΔE		3.88	8.56	2.3	4.53	**Sample** 8 ΔE		3.97	8.61	2.14	4.83
Mean		3.82	8.74	2.00	4.58	**Mean**		3.98	8.69	1.97	4.63
STDEV		0.42190	0.42016	0.27723	0.20760	**STDEV**		0.41935	0.39319	0.21567	0.16962

Measurement of A3 Tab and Veneer Combinations after a Three Hour Time Lapse

Table 3.1.6

A3 Tab No3 and veneers with Air					
	A3 Tab	Veneer	Veneer	Veneer	Veneer
Shade		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**
Sample 1 ΔE		3.28	8.91	1.63	4.48
Sample 2 ΔE		3.74	8.78	2.23	4.52
Sample 3 ΔE	**31.96**	4.19	9.26	2.1	5.04
Sample 4 ΔE		3.66	9.12	2.23	4.55
Sample 5 ΔE		3.69	8.78	1.67	4.33
Sample 6 ΔE		3.49	7.88	2.09	4.53
Sample 7 ΔE		4.63	8.61	1.72	4.67
Sample 8 ΔE		3.88	8.56	2.3	4.53
Mean		3.8	8.7	2.0	4.6
STDEV		0.42190	0.42016	0.27723	0.20760

Colour Difference Compared to Tab A3 No 3

Table 3.1.7

B1 Tab No5 and veneers with Air					
	B1 Tab	Veneer	Veneer	Veneer	Veneer
Shade		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**
Sample 1 ΔE		3.16	2.75	6.84	8.6
Sample 2 ΔE		2.48	2.75	7.87	8.86
Sample 3 ΔE		2.14	3.09	7.53	8.82
Sample 4 ΔE		2.74	2.53	7.78	8.86
Sample 5 ΔE	**25.54**	2.76	2.69	7.06	8.53
Sample 6 ΔE		3	1.9	7.68	8.69
Sample 7 ΔE		2.11	2.46	6.71	8.78
Sample 8 ΔE		2.88	2.4	7.65	8.73
Mean		2.7	2.6	7.4	8.7
STDEV		0.38465	0.34663	0.45160	0.12118

Colour Difference Compared to Tab B1 No 5

Table 3.1.8

B4 Tab No4 and veneers with Air					
	B4 Tab	Veneer	Veneer	Veneer	Veneer
Shade		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**
Sample 1 ΔE		8.85	14.03	5.41	5.89
Sample 2 ΔE		9.17	13.93	4.83	5.61
Sample 3 ΔE		9.61	14.08	4.98	5.73
Sample 4 ΔE	**37.75**	8.89	13.9	4.82	5.59
Sample 5 ΔE		8.98	13.77	5.35	6.19
Sample 6 ΔE		8.85	12.82	4.66	5.51
Sample 7 ΔE		9.75	13.51	5.64	5.65
Sample 8 ΔE		9.01	13.67	5.16	5.74
Mean		9.1	13.7	5.1	5.7
STDEV		0.35195	0.40725	0.34075	0.21563

Colour Difference Compared to Tab B4 No 4

Table 3.1.9

C4 Tab No4 and veneers with Air					
	C4 Tab	Veneer	Veneer	Veneer	Veneer
Shade		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**
Sample 1 ΔE		10.51	14.83	8.14	4.24
Sample 2 ΔE		10.42	14.69	8.22	4.3
Sample 3 ΔE		10.96	15.02	8.28	4.31
Sample 4 ΔE	**40.58**	10.69	14.96	8.23	4.31
Sample 5 ΔE		10.69	14.5	8.16	4.7
Sample 6 ΔE		10.58	13.39	8.06	4.02
Sample 7 ΔE		11.11	14.64	8.27	4.27
Sample 8 ΔE		10.66	14.58	8.43	4.26
Mean		10.7	14.6	8.2	4.3
STDEV		0.22877	0.51250	0.11070	0.18696

Colour Difference Compared to Tab C4 No 4

Table 3.1.10

Colour Measurement of Base Tabs & Veneers with Try-in Media

Each of the eight veneers of the four shade groups was placed over the representative shade tab of each of the four shades, with three different try-in mediums between them i.e. water, glycerine and base/try-in paste. The mean colour differences between the tab and veneer combinations and the base shade tab of the same shade as the veneer group for each medium were calculated.

The results for the water medium are shown in Tables 3.1.11, 3.1.12, 3.1.13 & 3.1.14.

The results for the glycerine medium are shown in Tables 3.1.15, 3.1.16, 3.1.17 & 3.1.18.

The results for the base/try-in paste medium are shown in Tables 3.1.19, 3.1.20, 3.1.21 & 3.1.22.

Statistical analysis of the colour differences, (ΔE), of each the base shade tab, veneer and media combinations was performed and the p values calculated. The results are shown in Tables 3.1.23, 3.1.24, 3.1.25 & 3.1.26.

Colour Difference of Veneers Shade A3, B1, B4 & C4 over Base Shade Tabs of A3, B1, B4 & C4, compared to the Representative Tab of the Same Shade.

Each of the eight veneers of the four shade groups was placed over the base shade tab of each of the four shades, with a water medium between them, and the colour compared to the representative base shade tab of the same shade as the veneer. The results can be seen in Tables 3.1.27, 3.1.28, 3.1.29 & 3.1.30.

A3 Tab No3 and veneers with Water					
	C4 Tab	Veneer	Veneer	Veneer	Veneer
Shade		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**
Sample 1 ΔE		2.23	4.99	3.85	7.68
Sample 2 ΔE		2.97	5.39	4.13	7.36
Sample 3 ΔE	**31.96**	3	5.11	3.48	7.14
Sample 4 ΔE		3.14	5.28	3.96	7.52
Sample 5 ΔE		2.56	5.31	4.1	7.39
Sample 6 ΔE		2.53	4.93	4.25	7.74
Sample 7 ΔE		2.62	4.78	3.66	7.55
Sample 8 ΔE		2.98	5.05	3.4	7.77
Mean		2.8	5.1	3.9	7.5
STDEV		0.31341	0.20922	0.31359	0.21524

Colour Difference Compared to Tab A3 No 3

Table 3.1.11

B1 Tab No5 and veneers with Water					
	C4 Tab	Veneer	Veneer	Veneer	Veneer
Shade		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**
Sample 1 ΔE		5.22	2.01	8.78	10.67
Sample 2 ΔE		5.74	1.63	9.34	10.8
Sample 3 ΔE		4.76	2.03	9.05	10.89
Sample 4 ΔE		5.01	1.84	9.24	10.71
Sample 5 ΔE	**25.54**	5.07	2.33	8.78	11.13
Sample 6 ΔE		4.66	2.72	9.16	10.73
Sample 7 ΔE		4.23	1.94	8.21	10.49
Sample 8 ΔE		5.19	2.32	8.49	10.7
Mean		5.0	2.1	8.9	10.8
STDEV		0.44744	0.34074	0.39088	0.18639

Colour Difference Compared to Tab B1 No 5

Table 3.1.12

B4 Tab No4 and veneers with Water					
	C4 Tab	Veneer	Veneer	Veneer	Veneer
Shade		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**
Sample 1 ΔE		5.26	8.37	2.59	6.13
Sample 2 ΔE		5.27	8.84	2.3	6.01
Sample 3 ΔE		5.85	8.51	2.34	6.41
Sample 4 ΔE	**37.75**	5.58	8.74	2.43	6.32
Sample 5 ΔE		5.42	8.31	2.79	6.34
Sample 6 ΔE		5.47	7.89	2.62	6.37
Sample 7 ΔE		5.67	8.28	2.64	6.42
Sample 8 ΔE		5.55	8.88	2.31	6.56
Mean		5.5	8.5	2.5	6.3
STDEV		0.19910	0.33534	0.19322	0.17353

Colour Difference Compared to Tab B4 No 4

Table 3.1.13

C4 Tab No4 and veneers with Water					
	C4 Tab	Veneer	Veneer	Veneer	Veneer
Shade		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**
Sample 1 ΔE		5.45	8.74	3.25	2.61
Sample 2 ΔE		4.68	8.43	3.77	2.41
Sample 3 ΔE		6.11	8.71	3.43	2.72
Sample 4 ΔE	**40.58**	5.52	8.84	3.84	2.56
Sample 5 ΔE		5.18	8.7	3.01	2.91
Sample 6 ΔE		5.85	7.69	2.92	2.6
Sample 7 ΔE		6.1	8.48	3.78	2.62
Sample 8 ΔE		5.83	8.6	3.68	2.63
Mean		5.6	8.5	3.5	2.6
STDEV		0.48937	0.36335	0.36457	0.14200

Colour Difference Compared to Tab C4 No 4

Table 3.1.14

A3 Tab No3 and veneers with Glycerine					
	A3 Tab	Veneer	Veneer	Veneer	Veneer
Shade		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**
Sample 1 ΔE		2.99	4.55	3.71	7.55
Sample 2 ΔE		3.38	4.72	3.6	7.47
Sample 3 ΔE	**31.96**	3.29	4.75	3.39	7.84
Sample 4 ΔE		3.12	4.85	4	7.47
Sample 5 ΔE		2.88	4.96	3.88	7.07
Sample 6 ΔE		2.91	4.69	4.09	7.87
Sample 7 ΔE		3.2	4.53	3.47	8.07
Sample 8 ΔE		3.11	4.69	3.69	7.4
Mean		3.1	4.7	3.7	7.6
STDEV		0.17760	0.14250	0.24701	0.31806

Colour Difference Compared to Tab A3 No 3

Table 3.1.15

B1 Tab No5 and veneers with Glycerine					
	B1 Tab	Veneer	Veneer	Veneer	Veneer
Shade		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**
Sample 1 ΔE		5.45	2.87	8.82	11.36
Sample 2 ΔE		5.21	2.59	9.3	11.19
Sample 3 ΔE		5.22	2.21	9.22	11.44
Sample 4 ΔE		5.26	2.41	9.26	11.26
Sample 5 ΔE	**25.54**	5.33	2.68	9.02	10.65
Sample 6 ΔE		5.57	3.27	9.3	11.49
Sample 7 ΔE		4.73	2.59	8.61	11.2
Sample 8 ΔE		5.24	2.81	9.14	11.41
Mean		5.3	2.7	9.1	11.3
STDEV		0.24550	0.31872	0.25196	0.26662

Colour Difference Compared to Tab B1 No 5

Table 3.1.16

B4 Tab No4 and veneers with Glycerine					
	B4 Tab	Veneer	Veneer	Veneer	Veneer
Shade		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**
Sample 1 ΔE		5.02	7.51	2.89	6.83
Sample 2 ΔE		4.76	7.74	2.52	6.43
Sample 3 ΔE		5.25	7.88	2.55	6.69
Sample 4 ΔE	**37.75**	5.22	8.2	2.54	6.48
Sample 5 ΔE		5.08	8.03	2.78	6.59
Sample 6 ΔE		4.8	7	2.72	6.69
Sample 7 ΔE		5.2	7.77	2.65	6.63
Sample 8 ΔE		5.1	7.73	2.33	6.63
Mean		5.1	7.7	2.6	6.6
STDEV		0.18601	0.36181	0.17515	0.12575

Colour Difference Compared to Tab B4 No 4

Table 3.1.17

C4 Tab No4 and veneers with Glycerine					
	C4 Tab	Veneer	Veneer	Veneer	Veneer
Shade		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**
Sample 1 ΔE		4.51	7.43	2.7	3.04
Sample 2 ΔE		3.95	7.62	3.06	2.97
Sample 3 ΔE		5.39	7.94	3	3.31
Sample 4 ΔE	**40.58**	4.82	7.68	2.9	3.09
Sample 5 ΔE		4.64	8	2.43	3.66
Sample 6 ΔE		4.46	7.05	2.71	2.88
Sample 7 ΔE		4.97	7.61	2.66	2.99
Sample 8 ΔE		4.42	7.95	3.38	3.12
Mean		4.6	7.7	2.9	3.1
STDEV		0.24806	0.31794	0.29384	0.24806

Colour Difference Compared to Tab C4 No 4

Table 3.1.18

A3 Tab No3 and veneers with Base/Try In Paste					
	A3 Tab	Veneer	Veneer	Veneer	Veneer
Shade		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**
Sample 1 ΔE		2.75	4.91	4.37	6.72
Sample 2 ΔE		3.1	4.74	4.5	7.61
Sample 3 ΔE	**31.96**	2.77	4.98	4.43	7.5
Sample 4 ΔE		2.73	4.53	4.32	7.48
Sample 5 ΔE		3.43	4.76	4.16	7.32
Sample 6 ΔE		2.74	4.34	4.53	7.79
Sample 7 ΔE		2.74	4.43	3.87	7.81
Sample 8 ΔE		2.68	4.52	4.48	7.91
Mean		2.9	4.7	4.3	7.5
STDEV		0.26196	0.23068	0.22154	0.37780

Colour Difference Compared to Tab A3 No 3

Table 3.1.19

B1 Tab No5 and veneers with Base/Try In Paste					
	B1 Tab	Veneer	Veneer	Veneer	Veneer
Shade		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**
Sample 1 ΔE		6.24	3.37	8.75	11.87
Sample 2 ΔE		6.04	3.09	9.35	11.4
Sample 3 ΔE		5.43	2.92	8.69	10.98
Sample 4 ΔE		5.75	2.76	9.13	11.36
Sample 5 ΔE	**25.54**	6.45	3.15	8.75	10.11
Sample 6 ΔE		5.97	3.45	9.12	11.47
Sample 7 ΔE		5.02	2.67	8.05	11.28
Sample 8 ΔE		5.52	2.86	9.42	11.32
Mean		5.8	3.0	8.9	11.2
STDEV		0.46733	0.28117	0.44487	0.51272

Colour Difference Compared to Tab B1 No 5

Table 3.1.20

B4 Tab No4 and veneers with Base/Try In Paste					
	B4 Tab	Veneer	Veneer	Veneer	Veneer
Shade		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**
Sample 1 ΔE		4.79	7.3	2.43	7.65
Sample 2 ΔE		4.49	7.86	2.11	6.32
Sample 3 ΔE		5.15	9.7	2.35	6.48
Sample 4 ΔE	**37.75**	5.02	7.77	2.22	6.27
Sample 5 ΔE		4.9	7.85	2.52	6.57
Sample 6 ΔE		4.92	6.99	2.23	6.21
Sample 7 ΔE		5.09	7.49	2.39	6.27
Sample 8 ΔE		5.01	7.75	2.08	6.28
Mean		4.9	7.8	2.3	6.5
STDEV		0.20774	0.81150	0.15634	0.47782

Colour Difference Compared to Tab B4 No 4

Table 3.1.21

C4 Tab No4 and veneers with Base/Try In Paste					
	C4 Tab	Veneer	Veneer	Veneer	Veneer
Shade		**A3 (0.5)**	**B1 (0.5)**	**B4 (0.5)**	**C4 (0.5)**
Sample 1 ΔE		4.61	6.93	1.86	3.43
Sample 2 ΔE		4.29	7.44	1.75	3
Sample 3 ΔE		5.08	8.5	1.67	3.31
Sample 4 ΔE	**40.58**	4.91	7.47	2.15	3.07
Sample 5 ΔE		4.39	7.32	1.67	3.54
Sample 6 ΔE		4.72	5.79	1.78	3.04
Sample 7 ΔE		5.18	7.13	1.93	3.15
Sample 8 ΔE		4.84	7.76	1.54	3.28
Mean		4.8	7.3	1.8	3.2
STDEV		0.31377	0.76960	0.18784	0.19492

Colour Difference Compared to Tab C4 No 4

Table 3.1.22

Shade Tab A3	*Air*				*Glycerine*				*Try-in Paste*			
With Veneer	A3	B1	B4	C4	A3	B1	B4	C4	A3	B1	B4	C4
A3 Air									0.0001			
A3 Water	0.0001				0.0018				0.0047			
A3 Glycerine	0.0001											
A3 Try-in Paste					0.3400							
B1 Air										0.0001		
B1 Water		0.0001				0.1400				0.5700		
B1 Glycerine		0.0001										
B1 Try-in Paste						0.1700						
B4 Air											0.0001	
B4 Water			0.0001				0.4000				0.0030	
B4 Glycerine			0.0001									
B4 Try-in Paste							0.0001					
C4 Air												0.0001
C4 Water				0.0001				0.4500				0.6200
C4 Glycerine				0.0001								
C4 Try-in Paste								0.9100				

Base Shade Tab A3 No 3 and Veneers with Air & Try-In Media
Shaded Cells Indicate P values ≥ 0.05 (no statistically significant difference)

Table 3.1.23

Shade Tab B1	*Air*				*Glycerine*				*Try-in Paste*			
With Veneer	A3	B1	B4	C4	A3	B1	B4	C4	A3	B1	B4	C4
A3 Air									0.0001			
A3 Water	0.0001				0.0140				0.0027			
A3 Glycerine	0.0001											
A3 Try-in Paste					0.1400							
B1 Air										0.0001		
B1 Water		0.0001				0.0001				0.0003		
B1 Glycerine		0.0001										
B1 Try-in Paste						0.0490						
B4 Air											0.0001	
B4 Water			0.0001				0.0320				0.8800	
B4 Glycerine			0.0001									
B4 Try-in Paste							0.3700					
C4 Air												0.0001
C4 Water				0.0001				0.0009				0.0450
C4 Glycerine				0.0001								
C4 Try-in Paste								0.8300				

Base Shade Tab B1 No 5 and Veneers with Air & Try-In Media
Shaded Cells Indicate P values ≥ 0.05 (no statistically significant difference)

Table 3.1.24

Shade Tab B4	*Air*				*Glycerine*				*Try-in Paste*			
With Veneer	A3	B1	B4	C4	A3	B1	B4	C4	A3	B1	B4	C4
A3 Air									0.0240			
A3 Water	0.0001				0.0028				0.0030			
A3 Glycerine	0.0330											
A3 Try-in Paste					0.2800							
B1 Air										0.0001		
B1 Water		0.0001				0.0200				0.4200		
B1 Glycerine		0.0001										
B1 Try-in Paste						0.5700						
B4 Air											0.0001	
B4 Water			0.0001				0.2900				0.0038	
B4 Glycerine			0.0001									
B4 Try-in Paste							0.2400					
C4 Air												0.0001
C4 Water				0.0001				0.0110				0.0350
C4 Glycerine				0.0001								
C4 Try-in Paste								0.2600				

Base Shade Tab B4 No 4 and Veneers with Air & Try-In Media
Shaded Cells Indicate P values ≥ 0.05 (no statistically significant difference)

Table 3.1.25

Shade Tab C4	*Air*				*Glycerine*				*Try-in Paste*			
With Veneer	A3	B1	B4	C4	A3	B1	B4	C4	A3	B1	B4	C4
A3 Air									0.0001			
A3 Water	0.0001				0.0023				0.0019			
A3 Glycerine	0.0001											
A3 Try-in Paste					0.8700							
B1 Air										0.0001		
B1 Water		0.0001				0.0005				0.0021		
B1 Glycerine		0.0001										
B1 Try-in Paste						0.1600						
B4 Air											0.0001	
B4 Water			0.0001				0.0026				0.0001	
B4 Glycerine			0.0001									
B4 Try-in Paste							0.0001					
C4 Air												0.0001
C4 Water				0.0001				0.0011				0.0001
C4 Glycerine				0.0001								
C4 Try-in Paste								0.0013				

Base Shade Tab C4 No 4 and Veneers with Air & Try-In Media
Shaded Cells Indicate P values ≥ 0.05 (no statistically significant difference)

Table 3.1.26

A3 Veneers with Water					
	Tab A3	**Tab A3 + Ven A3**	**Tab B1 + Ven A3**	**Tab B4 + Ven A3**	**Tab C4 + Ven A3**
Sample 1 ΔE		2.23	3.79	3.62	8.39
Sample 2 ΔE		2.97	4.1	4.31	9.22
Sample 3 ΔE	**31.96**	3	4.35	3.61	8.57
Sample 4 ΔE		3.14	4.15	3.81	8.66
Sample 5 ΔE		2.56	4.11	3.87	8.83
Sample 6 ΔE		2.53	3.95	3.41	7.98
Sample 7 ΔE		2.62	4.55	3.68	8.33
Sample 8 ΔE		2.98	4.08	3.72	8.26
Mean		2.8	4.1	3.8	8.5
STDEV		0.31341	0.23201	0.26441	0.38165

Colour Difference between A3 Veneer-Tab Combinations and Base Tab A3

Table 3.1.27

B1 Veneers with Water					
	Tab B1	**Tab A3 + Ven B1**	**Tab B1 + Ven B1**	**Tab B4 + Ven B1**	**Tab C4 + Ven B1**
Sample 1 ΔE		5.5	2.01	7.48	9.41
Sample 2 ΔE		5.08	1.63	6.99	9.9
Sample 3 ΔE		5.15	2.03	7.31	9.45
Sample 4 ΔE		4.81	1.84	7.06	8.98
Sample 5 ΔE	**25.54**	5.11	2.33	7.46	9.59
Sample 6 ΔE		6.53	2.72	8.02	10.76
Sample 7 ΔE		5.43	1.94	7.34	9.5
Sample 8 ΔE		5.28	2.32	6.74	9.66
Mean		5.4	2.1	7.3	9.7
STDEV		0.51924	0.34074	0.38645	0.51644

Colour Difference between B1 Veneer-Tab Combinations and Base Tab B1

Table 3.1.28

B4 Veneers with Water					
	Tab B4	**Tab A3 + Ven B4**	**Tab B1 + Ven B4**	**Tab B4 + Ven B4**	**Tab C4 + Ven B4**
Sample 1 ΔE		3.81	5.89	2.59	8.22
Sample 2 ΔE		3.24	5.24	2.3	7.51
Sample 3 ΔE		3.69	5.49	2.34	7.75
Sample 4 ΔE	**37.75**	3.37	5.31	2.43	7.57
Sample 5 ΔE		3.7	5.89	2.79	8.29
Sample 6 ΔE		3.43	5.48	2.62	8.07
Sample 7 ΔE		3.91	6.25	2.64	8
Sample 8 ΔE		3.6	5.97	2.31	7.55
Mean		3.6	5.7	2.5	7.9
STDEV		0.22972	0.35917	0.19322	0.31446

Colour Difference between B4 Veneer-Tab Combinations and Base Tab B4

Table 3.1.29

C4 Veneers with Water					
	Tab C4	**Tab A3 + Ven C4**	**Tab B1 + Ven C4**	**Tab B4 + Ven C4**	**Tab C4 + Ven C4**
Sample 1 ΔE		2.72	4.93	2.65	2.61
Sample 2 ΔE		3.08	4.88	2.79	2.41
Sample 3 ΔE		3.21	4.66	2.4	2.72
Sample 4 ΔE	**40.58**	2.91	4.92	2.52	2.56
Sample 5 ΔE		2.96	4.47	2.45	2.91
Sample 6 ΔE		2.71	4.9	2.44	2.6
Sample 7 ΔE		2.84	5.11	2.37	2.62
Sample 8 ΔE		2.67	4.86	2.32	2.63
Mean		2.9	4.8	2.5	2.6
STDEV		0.19122	0.19357	0.15673	0.14200

Colour Difference between C4 Veneer-Tab Combinations and Base Tab C4

Table 3.1.30

Assessment of the Clinical Significance of the Colour Difference between Veneer / Tab Combinations and the Base Shade Tabs.

The mean colour differences of each of the four veneers and base shade tab combinations compared to the base shade tabs of the same shade as the veneers were calculated. The results are shown in Table 3.1.31, with the shaded cells indicating a veneer shade capable of reproducing a clinically acceptable shade matching that of the representative base shade tab.

Mean Colour Differences between Tab and Veneer Combinations and Tabs				
	Veneer A3	Veneer B1	Veneer B4	Veneer C4
Tab A3	2.8	5.4	3.6	2.9
Tab B1	4.1	2.1	5.7	4.8
Tab B4	3.8	7.3	2.5	2.5
Tab C4	8.5	9.7	7.9	2.6

Shaded Cells Denote Clinically Acceptable Shade Matches

Table 3.1.31

CHAPTER FOUR: Discussion

The results of the colour analysis of the porcelain veneers of each of the two shades, A3 and A4 measured against black and white backgrounds, (Tables 3.1.1 & 3.1.2), show a greater mean ΔE colour difference between the two shades on the white background, (ΔE 8.19), compared with the black (ΔE 2.67). This may be because the black background absorbs more of the incident light, and therefore the magnitude of the reflected C.I.E. L*a*b* values are smaller than that of the white background resulting in smaller ΔE values (Berger-Schunn, 1994). This result is consistent with the findings of Grajower *et al*, (1982), and Cook and McAree (1985). In these studies, the magnitude of error for ΔE colour difference calculations between pairs of composite resin discs was greater for the black background than that of those measured on a white background. It has also been shown that samples measured on a white background will appear more chromatic compared with a black background (Powers *et al*, 1978). Clinically veneers are placed onto existing tooth structure and therefore the background colour is tooth coloured. The colour of human teeth is much closer to white than black and therefore it is more representative of intra-oral conditions if the veneers are measured against a white background. Following the results of the first part of this study it was decided to use a white background for all comparisons and measurements of all samples throughout the main study.

The manipulative variables involved when producing multiple custom-fabricated samples of the same shade were assessed by analysing the eight A3 base shade tabs on black and white backgrounds fabricated by the same operator. The results of this analysis show a smaller standard deviation for the samples measured on the white

background than those measured on the black. These findings are consistent with results shown in previous studies (Grajower *et al,* 1982). The comparatively low standard deviation illustrated by the analysis of the A3 tabs on the white background demonstrates consistent reproducibility of the colour of these samples. The extremely low standard deviation shown by the analysis of the thickness of the samples is accounted for by the meticulous but time consuming hand finishing of the sample surfaces by a single experienced operator. The same operator fabricated all samples, which may have contributed to the reproducibility and homogeneity of the colour and surface gloss of the samples. Other manipulative variables arising during fabrication, such as small changes in the temperature used in the main firing cycle necessary to produce the samples have little effect on the perceptible colour of the porcelain (Rosensteil and Johnston 1988, Barghi and Richardson 1978). The small differences in compaction of the porcelain introduced by the hand condensation method used during placement of the porcelain in the refractory moulds has also been shown to have a little influence on the colour of the sample (Rosensteil and Johnston 1988). The time and care taken to produce samples to this tolerance was necessary because of the influence that the variables of dimension and surface contour may have on the perceived colour of the samples. The same techniques were used to fabricate all base shade tabs and veneers throughout the study and the results show similar comparatively low standard deviations among groups of samples. The low standard deviation between the base shade tabs allowed the selection of a single tab from each group of five as representative of this shade. This permitted the analysis of fewer tab and veneer combinations.

One of the disadvantages in preparing the surface of the samples with 1200 grit and

having them planar parallel to one another is that this has a marked effect on the thickness of the media between them. This surface preparation has lead to a thickness of media between the tabs and veneers ranging from 4 to 14μm. O'Keefe and Powers, (1990) have stated that clinically the thickness of resin cements used for porcelain restorations is approximately 150 μm. In the case of the base/try-in paste media, there could be a difference of 135 μm between the *in vivo* and the *in vitro* situations produced in this study. As the base/try-in paste used in this study was coloured, a thicker layer approaching the clinical average may have had some effect on the final colour of the porcelain veneer-tab combinations. Balderamos *et al* (1997), have shown that base/try-in pastes of this dimension can have a mollifying effect on the colour of porcelain samples and can reduce the colour difference between pairs of samples. A spacer of 150 μm may have been used between the veneers and tabs and a custom jig produced to fabricate a try-in media simulating the clinical situation. Base/try-in media of this thickness were produced during trials prior to the main study, but were found to be extremely fragile and difficult to handle without distortion or fracture when placing between samples. To avoid these problems the base/try-in media would have to be light cured between the tabs and veneers to maintain this thickness. This would have necessitated production of a new tab and veneer for every measurement and would have been prohibitively time consuming, and possibly introduced greater variations within the samples.

A spectrophotometer was used in this study in preference to the colorimeters used by researchers in other similar studies because of its ability to detect metameric pairs,

and discern differences between pairs of samples under different light sources if necessary. The reproducibility of the colour measurement of samples by the Spectramatch GT Spectrophotometer was shown to be consistent, with no statistical differences between groups of the same samples measured at different intervals. During the initial testing of the spectrophotometer it was found that any small differences in the alignment of the veneers and tabs could lead to statistically significant differences in the detected colour. The spectrophotometer could detect a significant ΔE colour difference between two colour measurements of the same sample if the sample was rotated through 90^0 for the second measurement. In an attempt to minimise this variable, both samples were marked to facilitate alignment in the same orientation to each other during spectrophotometric analysis.

All of the samples measured with the air medium between the tabs and veneers displayed statistically significant differences when compared to the three try-in media (water, glycerine & base/try-in paste).

This may be explained by the differences in the light refractive indices of air and the try-in media. The incident light passes through the veneer as it travels to the base tabs, the medium between them bends or refracts the incident light and also the reflected light. This is because the velocity of light is different for each transparent or translucent material it passes through. The velocity of light travelling through air is 300,000 Km per second, and the refractive index of any other material is calculated by dividing the velocity of light in air by the velocity in the material. Using this calculation the refractive index of water is found to be 1.333, feldspathic

porcelain is 1.504, and quartz filled dental composite is 1.540 (O'Brien, 1997). The perceived colour of any material is affected by the refractive index of any intermediate material because the bending of the incident light affects the shorter wavelengths to a greater extent than the longer wavelengths.

In the major part of the study it was decided to select only one of the three try-in media to analyse the clinical significance of the colour change effected by the porcelain veneer on the base shade tab. Air as a try-in media was discounted because of the statistically significant differences between air and the other three try-in media shown in the earlier part of the study.

The results of the statistical analysis of the comparisons between the three try-in media showed a better agreement between the glycerine versus base/try-in paste samples compared to the other two (water v glycerine & water v base/try-in paste). This may be caused by the differences in the refractive indices of the three materials or the colour of filler particles in the base/try-in paste.

Distilled water was used as the medium of choice between the tabs and veneers in the major part of this study, primarily because it was relatively easy to remove from the samples between colour measurements. The mean standard deviations of the analysis of the tab and veneer combinations with the base/try-in medium were higher than water or glycerine, (water- 0.291, glycerine- 0.270 & base/try-in paste 0.391). The mean standard deviations of glycerine were slightly lower than water, but the glycerine medium had to be steam-cleaned from the samples between measurements, as did the base/try-in paste, to remove any residue. It was decided not to use glycerine or base/try-in media as this would have involved an excessive amount of preparation time compared to simply removing the water medium with a clean dry

tissue.

The upper limit of C.I.E. L*a*b* ΔE colour difference units of a clinically acceptable shade match was accepted as ΔE 3.7 units, as shown in a previous intra-oral study of composite resin veneers (Johnston and Kao, 1989). Other research comparing spectrophotometric measurements with visual assessments of composite resin veneers have stated a figure of ΔE 3.3 units as a clinically acceptable shade match (Ruyter *et al*, 1987). The value of ΔE 3.7 was used in favour of the acceptable colour difference of ΔE 3.3 cited by Ruyter *et al*, (1987), as this was determined under laboratory conditions.

The results show that all four of the veneer shades measured were capable of producing a clinically acceptable shade match when placed over base tabs of the shade compared with the same base tab shade. The recorded colour differences for all four results of this comparison reveal colour differences greater than ΔE 2 units, ranging from ΔE 2.1 to 2.8 units. The American Dental Association advises that the maximum colour difference between two shade guide tabs of the same shade for any stated material should be no greater than C.I.E. ΔE 2 units (Wozniak, 1987). The magnitude of the colour difference between the base shade tabs with veneers of the same shade, and the base shade tab of the same shade may be explained by the change in the path of the incident light at the veneer/tab interface (Grajower *et al*, 1982). The base shade tabs and veneers, although made from the same material, are two physically separate entities and not one homogenous mass and the light is therefore refracted between the two causing colour differences. The inclusion of a water medium between the veneers and base shade tabs introduces a change in the

refractive index of light as it passes between them, which could result in colour differences.

The lighter shaded veneers of B1, and the mid range shade of A3, have less chroma than the B4 or C4 and were not capable of masking the underlying shade sufficiently to reproduce the veneer colour when placed over base shade tabs of any of the other three shades. The two darker shades of veneers analysed, (B4 and C4), were capable of producing a clinically acceptable shade match when placed over A3 in the case of B4, and A3 and B4 in the case of C4. The darker shades of porcelain veneer have a higher chroma than the lighter shades, and are capable of producing a greater masking effect on the underlying base shade. The masking effect of the darker veneers may only be sufficient to give a clinically acceptable shade match with shades close to the shade of the veneer with similar lightness or chroma values.

When a porcelain laminate veneer is utilised to improve the aesthetics of malaligned teeth, close diastemas or extend peg laterals, the shade of the underlying tooth may be prescribed. The results of this study show that it is probable that an aesthetically acceptable shade match to the existing tooth should be expected.

Clinically porcelain laminate veneers are widely used to improve the aesthetics of patients' teeth by lightening a discoloured tooth to bring the colour closer to the adjacent natural teeth. This study has shown that only the darker shades of porcelain laminate veneer are capable of replicating acceptable shade matches to the veneer if the underlying tab shade is not the same as the veneer. The lighter shades could not mask a different underlying shade sufficiently to reproduce the shade of the laminate prescribed. This may indicate that in order to produce a specific shade with a combination of tooth and a porcelain laminate veneer of 0.5mm that the clinician will

have to select a shade of veneer that is not the shade of the adjacent teeth. This may be an important finding, as the present method of shade prescription for porcelain laminate veneers generally involves detection of the shade of the adjacent teeth and prescribing that shade for the laminate. The results of this study indicate that this may not result in an aesthetically acceptable restoration for patient or clinician. The prospects of an aesthetically acceptable restoration may be increased if the clinician were to detect the shade of the discoloured tooth and also the shade of the adjacent teeth. With the aid of the information provided by Table 3.1.31, (or an expanded version of this study encompassing all sixteen Vita Lumin Vacuum shade combinations) the clinician may be more able to decide whether the combination of tooth and restoration is liable to give an aesthetically acceptable shade match.

Conclusions

The Spectramatch GT spectrophotometer was capable of detecting small colour differences between the adjacent shades of A3 and A4 Shofu Vintage Body Porcelain 0.5mm laminate veneers.

There were statistically significant differences between air and all three other try-in media i.e. distilled water, glycerine and base try-in paste.

There were no statistically significant differences among the other try-in media.

A3, B1, B4 & C4 shades of Shofu Vintage Body Porcelain.0.5mm veneers are capable of producing a clinically acceptable shade match to the base shade tab of the same shade, when placed over the base shade tabs of that same shade.

Shade B4 Shofu Vintage Body Porcelain.0.5mm veneers were capable of reproducing an acceptable shade match to the B4 base shade tab when placed over shade A3 base shade tabs.

Shade C4 Shofu Vintage Body Porcelain.0.5mm veneers were capable of producing an acceptable shade match to the C4 base shade tab when placed over A3 and B4 base shade tabs.

Recommendations for Future Studies

The evidence in this study of the effect of the four Shofu Vintage Body Porcelain shades of veneer and tab combinations analysed, justify investigation of all sixteen Shofu Vintage Body Porcelain shades, and possibly the inclusion of Shofu Vintage Enamel Porcelain shades in a future study.

A future study should investigate the magnitude and direction of the C.I.E. L*a*b* parameters effected by the veneers on the base shade tabs.

The colour of dental porcelain veneer materials from other manufacturers should also be investigated.

REFERENCES

Balderamos, L.P., O'Keefe, K.L., Powers, J.M. (1997) Colour accuracy of resin cements and try-in pastes. *The International Journal of Prosthodontics* **10**, (2) 111-115.

Bangston, L.K. and Goodkind, R.J. (1982) The conversion of Chromascan designations to CIE tristimulus values. *The Journal of Prosthetic Dentistry* **48**, 610-617.

Barghi, N. and Richardson, J.T. (1978) A study of various factors influencing shade of bonded porcelain. *The Journal of Prosthetic Dentistry* **39**, 282-284.

Barna, G.J., Taylor, J.W., King, G.E. and Pelleu, G.B. (1981) The influence of selected light intensities on color perception within the color range of natural teeth. *The Journal of Prosthetic Dentistry* **46**, 450-453.

Bergen, S.F. and McCasland, J. (1977) Dental operatory lighting and tooth color discrimination. *Journal of the American Dental Association* **94**, 130-134.

Berger-Schunn, A. (1994) *Practical Colour Measurement*, New York: John Wiley & Sons.

Boyer, D.B. (1982) Bonding between acrylic laminates and composite resin veneers. *Journal Dental of Research* **61**, 489-492.

Buonocore, M.A. (1955) A simple method of increasing the adhesion of acrylic fillings to enamel surfaces. *Journal Dental of Research* **34**, 849-853.

Calamia, J.R. (1983) Etched porcelain facial veneers: a new treatment modality based on scientific and clinical evidence. *New York Journal of Dentistry* **53**, 255-259.

Calamia, J.R. (1985) Etched porcelain veneers: the current state of the art. *Quintessence International* **1**, 5-12.

Chalkley, Y.M. and Jensen, M.E. (1984) Enamel shear bond strength of a dentinal bonding agent. *Journal Dental of Research* **63**, 320

Clark, E.B. (1931a) An analysis of tooth color. *Journal of the American Dental Association* 2093-2103.

Clark, E.B. (1931b) The Clark tooth color system. Part I. *The Dental Magazine and Oral Topics* 138-152.

Clark, E.B. (1933) Tooth color selection. *Journal of the American Dental Association* 1065-1073.

Clark, E.B. (1947) Selection of tooth color for the edentulous patient. *Journal of the American Dental Association* **35**, 787-793.

Cook, W.D. and McAree, D.C. (1985) Optical properties of esthetic restorative materials and natural dentition. *Journal of Biomedical Materials Research* **19**, 469-488.

Croll, T.P. (1989) Enamel microabrasion for removal of superficial enamel discolouration. *Journal of Esthetic Dentistry* **1**, 14-20.

Culpepper, W.D. (1970) A comparative study of shade-matching procedures. *The Journal of Prosthetic Dentistry* **24**, 166-173.

Donahue, J.l., Goodkind, R.J., Schwabacher, W.R. and Aeppli, D.P. (1991) Shade colour discrimination by men and women. *The Journal of Prosthetic Dentistry* **65**, 699-703.

Douglas, R.D. and Brewer, J.D. (1998) Acceptibility of shade differences in metal ceramic crowns. *The Journal of Prosthetic Dentistry* **79**, 254-260.

Doulgas, R.D. (1997) Precision of in vivo colorimetric assessments of teeth. *The Journal of Prosthetic Dentistry* **77**, 464-470.

Dvorine, I. (1953) Dvorine Pseudo-Isochromatic Plate Test. *The Psychological Corp*, New York, NY, USA

Farnsworth, D. (1957) *Farnsworth Colour Manual*, Baltimore: Munsell Colour Company Inc.

Faunce, F.R. (1976) Laminate veneer restoration of permanent incisors. *Journal of the American Dental Association* **93**, 790

Faunce, F.R. (1977) Tooth restoration with preformed laminated veneers. *Dental Survey* **53**, 70

Freedman, G.A. and McLaughlin, G.L. (1990) *Color atlas of porcelain laminate veneers.* St.Louis: Ishiyaku EuroAmerica, Inc.

Goldstein, G.R. and Schmitt, G.W. (1993) Repeatability of a specially designed intraoral colorimeter. *The Journal of Prosthetic Dentistry* **69**, 616-619.

Goldstein, R.E. (1997) In-office bleaching: where we came from, where we are today. *Journal of the American Dental Association* **128**, 11s-15s.

Goodkind, R.J., Keenan, K.M. and Schwabacher, W.R. (1985) A comparison of Chromascan and spectrophotometric colour measurement of 100 natural teeth. *The Journal of Prosthetic Dentistry* **53**, 105-109.

Goodkind, R.J. and Schwabacher, W.R. (1987) Use of a fibre-optic colorimeter for in vivo color measruements of 2830 anterior teeth. *The Journal of Prosthetic Dentistry* **58**, 535-542.

Grajower, R., Wozniak, W.T. and Lindsay, J.M. (1982) Optical properties of composite resins. *Journal of Oral Rehabilitation* **9**, 389-399.

Hayashi, T. (1967) Medical colour standard tooth crown. *Japan Research Institute*

Haywood, V.B. (1997) Nightguard vital bleaching: current concepts and research. *Journal of the American Dental Association* **128**, 19s-25s.

Horn, H.R. (1983a) Porcelain laminate veneers bonded to etched enamel. *Dental Clinics of North America* **27**, 671-684.

Horn, H.R. (1983b) A new lamination: porcelain bonded to enamel. *New York State Dental Journal* **49**, 401-403.

Ishikawa, T., Ohsone, M. and Sekine, N. (1969) Trial manufacture of photoelectric colorimeter using optical fibres. *Bulliten of the Tokyo Dental College* **10**, 191

Johnston, W.M. and Kao, E.C. (1989) Assessment of appearance match by visual observation and clinical colorimetry. *Journal Dental of Research* **68**, 819-822.

Jordan, R.E. (1993) *Esthetic composite bonding: techniques and materials.* 2nd edn. St. Louis: Mosby Year Book.

Jordan, R.E., Suzuki, M. and Croll, T.P. (1992) Conservative Treatment of the Discoloured Dentition. In: Jordan, R.E. (Ed.) *Esthetic Composite Bonding*, 2nd edn. pp. 84-162. Mosby Year Book

Kelly, J.R., Nishimura, I., Campbell, S.D. (1996) Ceramics in Dentistry: Historical roots and current perspectives. *Journal of Prosthetic Dentistry* **75** 18-32.

Lemire, P.A. and Burk, B. (1974) *Colour in dentistry*, Hartford: Ney.

Macentee, M. and Lakowski, R. (1981) Instrumental color measurement of vital and extracted human teeth. *Journal of Oral Rehabilitation* **8**, 203-208.

McLaughlin, G. (1984) Porcelain fused to tooth: a new esthetic and reconstructive modality. *Compendium of Continuing Education in Dentistry* **5**, 430-436.

McLean, J.W. (1979) *The Science and Art of Dental Ceramics*, Chicago: Quintessence Publishing Co.,Inc.

Miller, L. (1987) Organizing color in dentistry. *Journal of the American Dental Association*, Special Issue, 26-E-40-E.

Miller, L. (1994) Shade selection. *Journal of Esthetic Dentistry* **6**, 47-60.

Moser, J.B., Wozniak, W.T., Naleway, C.A. and Ayer, W.A. (1985) Colour vision in dentistry: a survey. *Journal of the American Dental Association* **110**, 509-510.

Munsell, A.H. (1926) A Colour Notation. In: Anonymous *A Colour Notation*, Baltimore, Md

O'Brien, W.J. (1997) *Dental Materials and Their Selection*, 2nd edn. Chicago: Quintessence Publishing Co.,Inc.

O'Brien, W.J., Boenke, K.M. and Groh, C.L. (1991) Coverage error of two shade guides. *The International Journal of Prosthodontics* **4**, 45-50.

O'Keefe, K.L., Powers, J.M. (1990) Light-cured resin cements for the cementation of esthetic restorations. *Journal of Esthetic Dentistry* **2**, 129-133.

Pincus, C.L. (1938) Building mouth personality. *Journal of the Californian Dental Association* **14**, 125-129.

Powers, J.M., Dennison, J.B. and Lepeak, P.J. (1978) Parameters that affect the color of direct restorative resins. *Journal Dental of Research* **57**, 876-880.

Rochette, A.L. (1975) A ceramic restoration bonded by etched enamel and resin for fractured incisors. *The Journal of Prosthetic Dentistry* **33**, 287-293.

Rosensteil, S.F. and Johnston, W.M. (1988) The effects of manipulative variables on the colour of ceramic metal restorations. *The Journal of Prosthetic Dentistry* **60**, 297-303.

Rotstein, I., Zalkind, M., Mor, C., Tarabeah, A. and Freidman, S. (1991) In vitro efficacy of sodium perborate preparations used for intracoronal bleaching of discoloured teeth. *Endodontics and Dental Traumatology* **7**, 177-180.

Ruyter, I.E., Nilner, K. and Moller, B. (1987) Color stability of dental composite resin materials for crown and bridge veneers. *Dental Materials* **3**, 246-251.

Saleski, C.G. (1972) Color, light and shade matching. *The Journal of Prosthetic Dentistry* **27**, 263-268.

Schwabacher, W.R. and Goodkind, R.J. (1990) Three-dimensional colour coordinates of natural teeth compared with three shade guides. *The Journal of Prosthetic Dentistry* **64**, 425-431.

Sebor, R.J. (1983) Restoration of class IV lesions and fractures with acid etched composite. *Compendium of Continuing Education in Dentistry* **4**, 510-516.

Simonsen, R.J. and Calamia, J.R. (1983) Tensile bond strength of etched porcelain. *Journal Dental of Research* **62**, 297(Abstract)

Sproull, R.C. (1967) A survey of colour education in the dental schools of the world. El Paso, Texas: U.S. Army.

Sproull, R.C. (1973) Color matching in dentistry. Part I. The three-dimensional nature of color. *The Journal of Prosthetic Dentistry* **29**, 416-424.

Swift, E.J., Hammel, S.A. and Lund, P.S. (1994) Colorimetric evaluation of Vita shade resin composites. *The International Journal of Prosthodontics* **7**, 356-361.

Tsuchiya, K. (1973) A colorimetric study of anterior teeth. *Shikwa Gakuho* **72**, 87

van der Burgt, T.P., ten Bosch, J.J., Borsboom, P.C.F. and Plasschaert, J.M. (1985) A new method for matching tooth colors with color standards. *Journal of Dental Research* **64**, 837-841.

Wasson, W. and Schuman, N. (1992) Colour vision and dentistry. *Quintessence International* **23**, 349-353.

Wozniak, W.T. (1987) Proposed guidelines for the acceptance program for dental shade guides. Chicago: American Dental Association.

Yamamoto, M. (1998) Development of the Vintage Halo Computer Color Search System. *Quintessence of Dental Technology* 9-26.